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ORIGINAL ARTICLES.

The Form and Age of the Greenland Ice Cap.

By L. R. WAGER, Lecturer in Petrology, Reading University.

(PLATES X–XII.)

THE first crossing of the Greenland Ice Cap by Fridjof Nansen in 1888 had shown that the southern part was a flattened dome rising to a height of 2,720 m. Crossings in 1912 by the Danish expedition of J. P. Koch and A. Wegener and by a Swiss expedition under de Quervain proved that there was a northern culmination, reaching to a height of at least 3,000 m., which was separated by a saddle of about 2,500 m. from the southern culmination traversed by Nansen. The form of the Ice Cap determined by these three crossings and by other expeditions near its margin of Rink, Jensen, Baron Nordenskiöld, Peary, Gaarde, Mikkelsen, Rasmussen, and L. Koch, has been summarized in sketch-maps by L. Koch (1923) [1] and de Quervain (1925).[1] In the year 1930–31 several expeditions were simultaneously making further contributions to our knowledge of the Greenland Ice Cap. (See Fig. 1.) A German expedition, led by Alfred Wegener, established a station, from a base on the west coast, at about the centre of the Ice Cap, and from here glaciological and meteorological observations were made throughout the year. The British Arctic Air-Route Expedition, led by the late H. G. Watkins, had a base on the east coast in the Angmagsalik District from which several journeys on the Ice Cap were made, and an Ice Cap Station, some 200 miles from the coast, was maintained for meteorological work. The primary object of Watkins' Expedition (1932) was to decide on the possibilities of establishing an air route across the saddle in the Ice Cap surface, but the results also contributed to various scientific problems connected with Greenland. Of minor expeditions, during the recent renewed investigations on the Ice Cap, one under

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[1] References at end of paper.

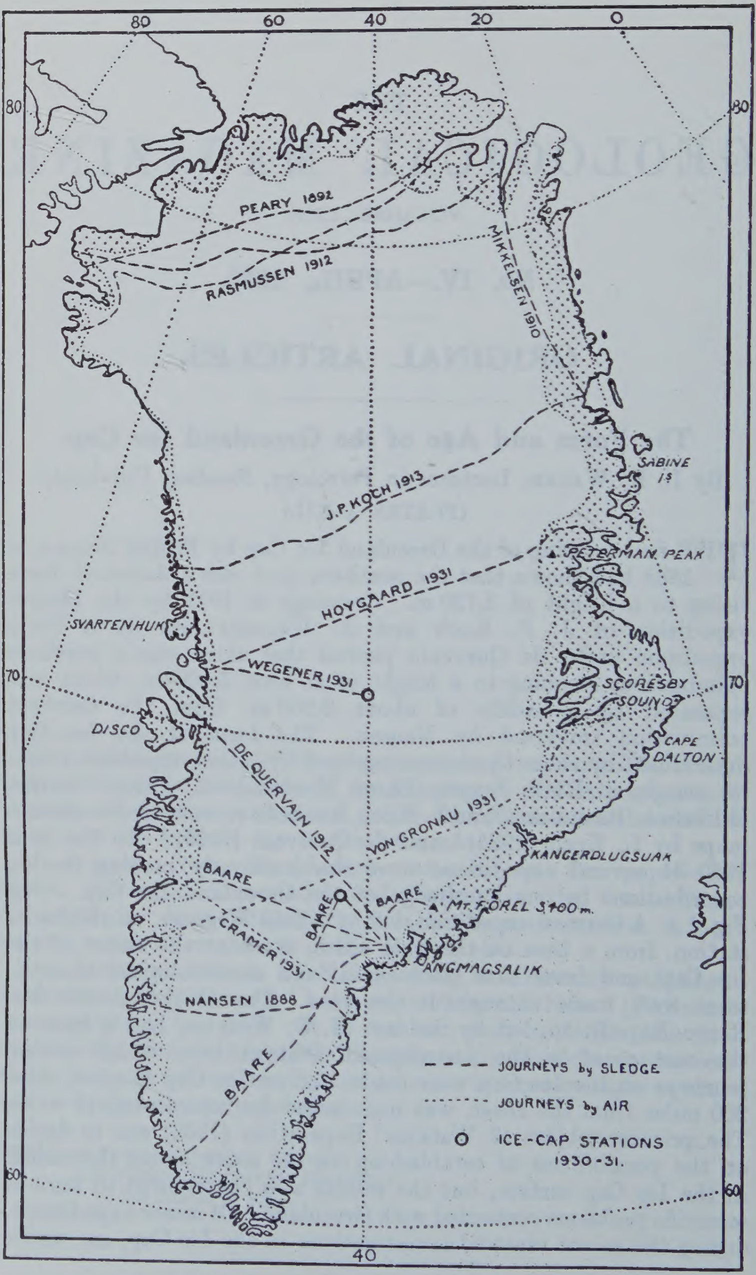

Fig. 1.—Sketch-map showing main expeditions on the Ice Cap and the localities mentioned in the text. BAARE stands for British Arctic Air-Route Expedition journeys.

Hoygaard in the summer of 1931 crossed by sledge the northern culmination and extended our knowledge of its form, while during the same summer Cramer made a crossing by air over the saddle in the Ice Cap and von Grunau made another crossing by air over the northern culmination.

CONTOURS OF THE INLAND ICE SURFACE.

The maps of L. Koch (1923) and de Quervain (1925) form the basis of the contoured sketch-map of the Ice Cap given here (Fig. 2). For the northern third of the Ice Cap the contours are taken without change from L. Koch's map, but for the southern two-thirds the contours are considerably modified on the basis of the recent journeys. The crossing by Hoygaard's party and the well-established height of Wegener's centre station enable the 3,000 m. contour to be continued with certainty to the neighbourhood of Mt. Forel across the region between Scoresby Sound and Disco Bucht, which was postulated as a depression by L. Koch in 1923. Hoygaard's journey has also shown that the northern culmination is much nearer the east than the west coast. On the journey to Mt. Forel during Watkins' Expedition the highest known part of the Ice Cap was discovered. During an attempt to reach the summit of the mountain the climbing party, Stephenson and the writer, were able to look N.W. from a height of 3,200 m. over the Ice Cap which was higher than they were, and therefore probably at least 3,300 m. above sea-level. Other journeys during the British Arctic Air-Route Expedition (Watkins, 1932) established more exactly the position of the saddle which is at least as low as 2,400 m.,[1] and showed that the southern culmination, which rises to 2,800 m., is more to the south and east than was formerly believed. Von Grunau's crossing of the Inland Ice by air, flights of the British Arctic Air-Route Expedition, Hoygaard's Sledging Expedition, and now Ejnar Mikkelsen's 1932 Expedition to the Blossville coast and Kangerdlugsuak have further defined the limit between the Inland Ice and the coastal mountain belt in latitude 65°-70°, and have shown that it lies far to the west of the previously conjectured boundary. (See Fig. 2.)

The factors controlling the form of an ice sheet are still a matter of doubt. It is not clear, for instance, how much the extent and thickness of an ice sheet is due to the form of the underlying land surface, how much it is due to the climatic factors of precipitation,

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[1] There is some doubt about the height reached at a point some 60 miles S.W. of the Ice Cap Station during the B.A.A.R.E. crossing to Holsteinbourg. There were anomalies in the barometer readings, and hence there is a possibility, as assumed by Stephenson (1932), of a rather sudden rise to 2,800 m. and an equally sudden fall. Such a ridge should have been noticeable on the ground and perhaps even crevassed. Mr. Mirrlees, of the Meteorological Office, has kindly gone into the evidence again but has not been able to decide between the possibility assumed by Stephenson and the possibility assumed here.

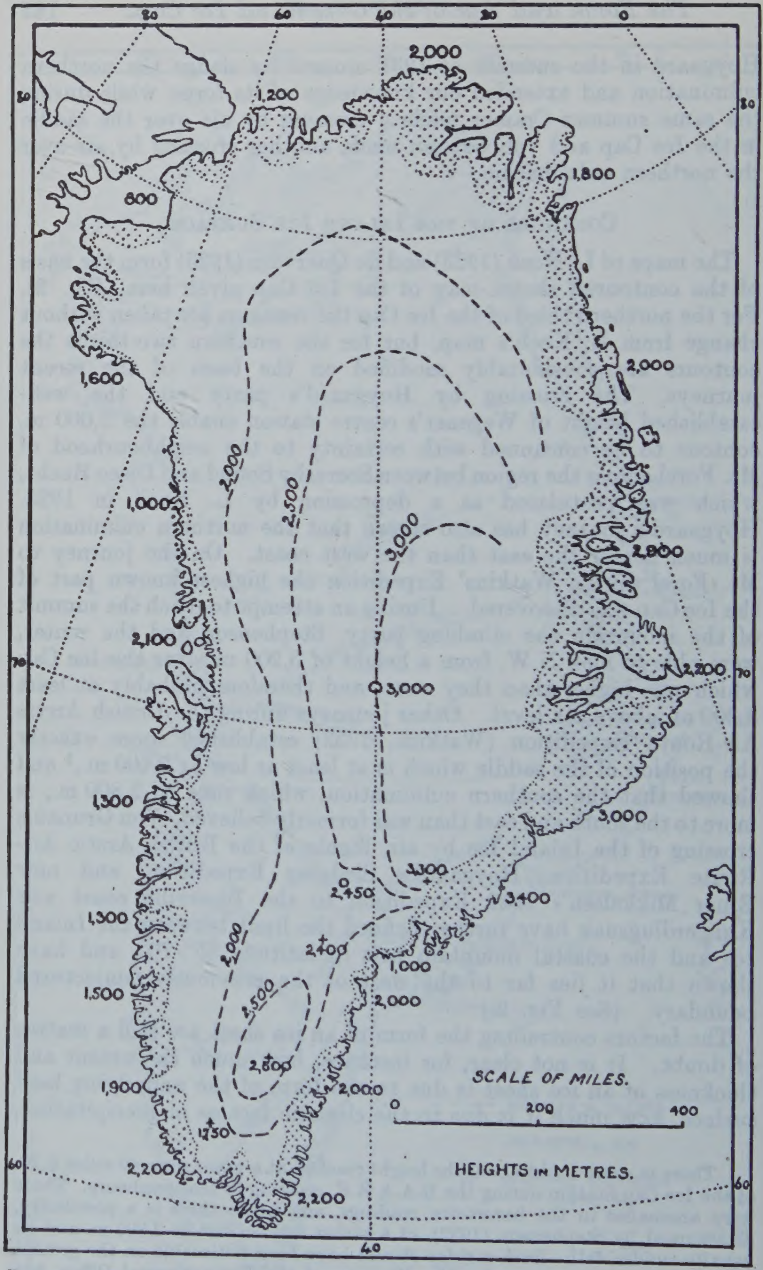
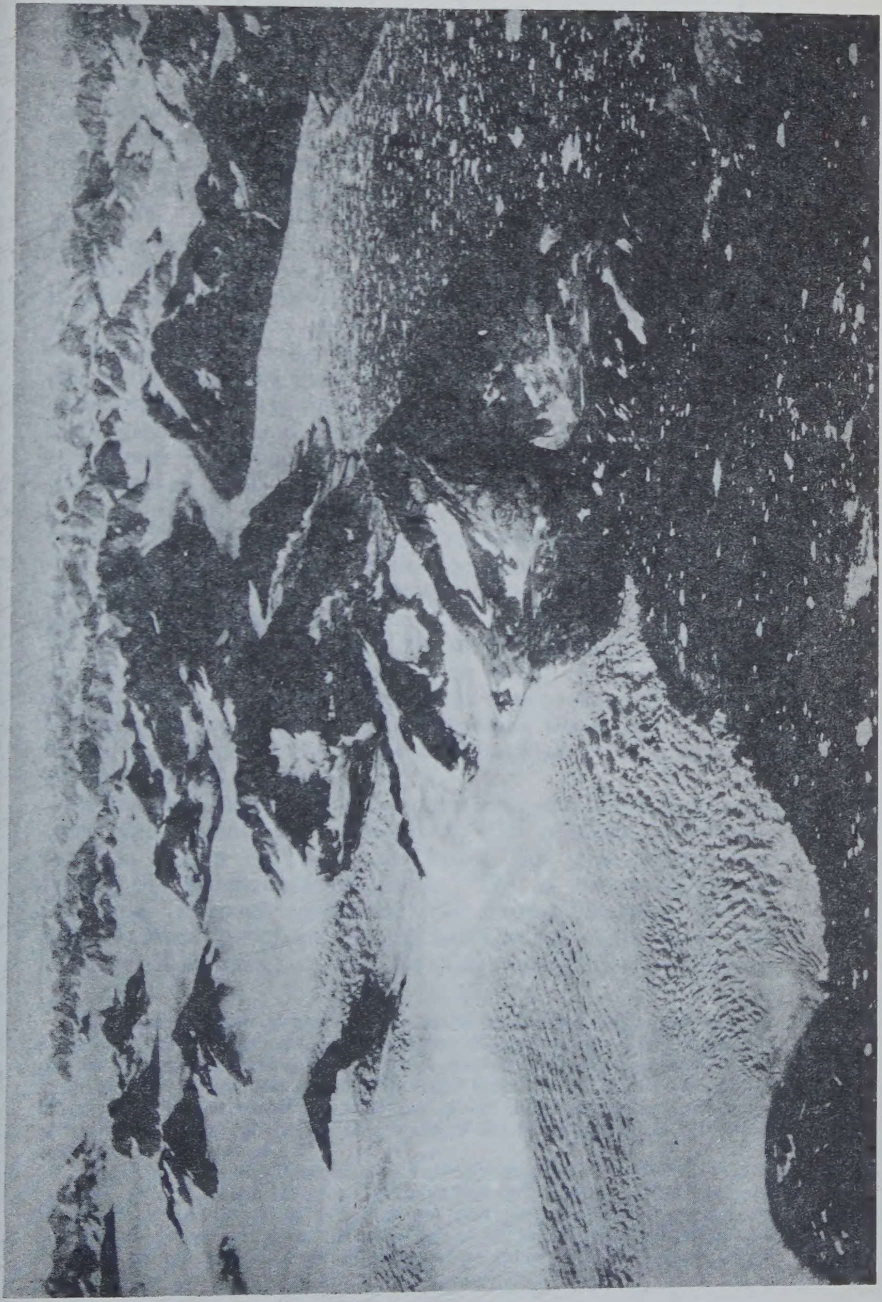


FIG. 2.—Map showing contours of the Greenland Ice Cap based on data collected by all expeditions up to the end of 1931. Figures off the coast give the height in metres of the highest mountains of the various coastal districts. The dotted area represents the region where solid rock projects; the undotted area represents the unbroken Ice Cap.



COASTAL MOUNTAINS S. OF KANGERDLUGSUAK

[*To face p.* 148.

ablation, and the removal of ice and snow by katabatic winds, or how much it depends on the physical properties of ice in the mass. On the sketch-map, Fig. 2, is given the height of the highest coastal mountains of the various districts based on the latest information, and it can at once be seen that, with few exceptions, the higher parts of the Ice Cap are adjacent to the higher coastal mountains, while the lower parts of the Ice Cap, and particularly the saddle between the two culminations, correspond to a relatively low coastal zone. This relationship was suggested, but by no means definitely, by the earlier maps of the Ice Cap by Koch and de Quervain.

If the general level of the coastal mountains is imagined to extend inwards under the Inland Ice, the reasonable conclusion is reached that the higher parts of the Ice Cap are covering what, on this hypothesis, should be the higher parts of the land surface. However, one of the most significant results of Wegener's Expedition is the demonstration by an echo-sounding method that beneath their station at the centre of the Greenland ice sheet, there is probably [1] a thickness of 2,500 m. of ice before the rock foundation is reached (E. Wegener, 1932). The land surface beneath the Inland Ice is therefore only about 500 m. above sea-level, although by extrapolation of the heights of the coastal mountains it would be expected to be 2,000–2,500 m. high. This depression is presumably mainly the result of isostatic adjustment due to the loading with ice [2] and takes place gradually with increasing distance from the margin. No doubt the development and the initial height of the Greenland ice sheet was a direct function of the height of the original land surface, but it is suggested that, at the present stage of its history, the essential topographic factor controlling the height of the Ice Cap is the height of the coastal mountain belt through which the excess of ice has to escape.

In the 600 miles of coastal mountains extending northwards from Angmagsalik and adjacent to the northern culmination there is known only one low broad gap, namely that containing the Kangerdlugsuak glacier. The ice drawn off through this gap, although producing the largest icebergs of this part of East Greenland, is not sufficient to cause more than a slight depression of the Ice Cap immediately round the head of the glacier. On the rest of the coast the ice overflows through high and usually narrow passes in the coastal mountain zone (Pl. X), and is then carried seawards by what are essentially valley glaciers of the coastal belt. Apparently the Ice Cap behind the coastal mountains piles itself up until such overflow is possible. The southern culmination is related in a similar way to high coastal mountains, but it seems to rise relatively higher above the average height of these mountains than does the northern culmination. Perhaps in this is to be seen the effect of greater precipitation, but, on the other hand, the height of the southern East Greenland mountains may be greater than at present believed. The saddle between the two culminations is apparently due to the easy escape of the ice over the low coastal mountains on the east coast S.W. of Angmagsalik (Pl. XI), and over relatively low coastal mountains in the same latitudes on the west coast.

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[1] The measurements could only be made in the few days preceding the abandoning of the Eismitte because of the disorganization of the expedition due to the death of Wegener. Only one measurement was completed at the Eismitte, about which the investigator states that it was " so gut wie sicher ", but the fifty measurements of a west coast group point clearly to the thickness of ice at the centre of the Ice Cap being of the order suggested by the one completed measurement.

[2] The amount of the depression is actually more than would at first be expected from isostatic theories. Perhaps the full account of the results of Wegener's Expedition, which is not yet published, will explain this, but I would tentatively suggest that the height of the coastal mountains has increased as valleys have been cut deeper into them. (Cf. F. Nansen, 1928.)

THE AGE OF THE ICE CAP.

In West Greenland, from Disco to Svartenhuk, sediments of Upper Cretaceous to Lower Eocene Age are found ; in East Greenland thin marine Lower Eocene deposits occur associated with basalts at Cape Dalton, 80 miles south of Scoresby Sound, and plant-bearing beds of probably the same age also occur at Sabine Island, 300 miles north of Scoresby Sound.[1] So far no sedimentary deposits have been found which record the middle and late Tertiary history of Greenland. During that time Greenland must have been essentially a region of uplift whose geological history will have to be read in the records of erosion ; and such records always seem to be more difficult to interpret and more incomplete than the records of sedimentation.

Seward (1926) has suggested that the fossil plants associated with the Upper Cretaceous and Lower Eocene deposits of West Greenland indicate a climate like that of Southern Europe to-day ; Ravn (1904) has not ventured to make an estimate of the climate which is indicated by the Lower Tertiary marine fauna of Cape Dalton, but he has shown a close similarity between this fauna and that of the London Clay, and perhaps it is legitimate to postulate much the same climatic conditions ; a recent study by Mathiesen (1932) of plant remains from the Tertiary of East Greenland has not prompted any direct statement about the climatic conditions, but the evidence no doubt points to Seward's view. Thus it is highly improbable that the Greenland area supported an ice sheet in Upper Cretaceous and Lower Eocene times, and the problem arises of the time of inception of the Greenland Ice Cap.

The persistence to-day of the Greenland ice sheet while the

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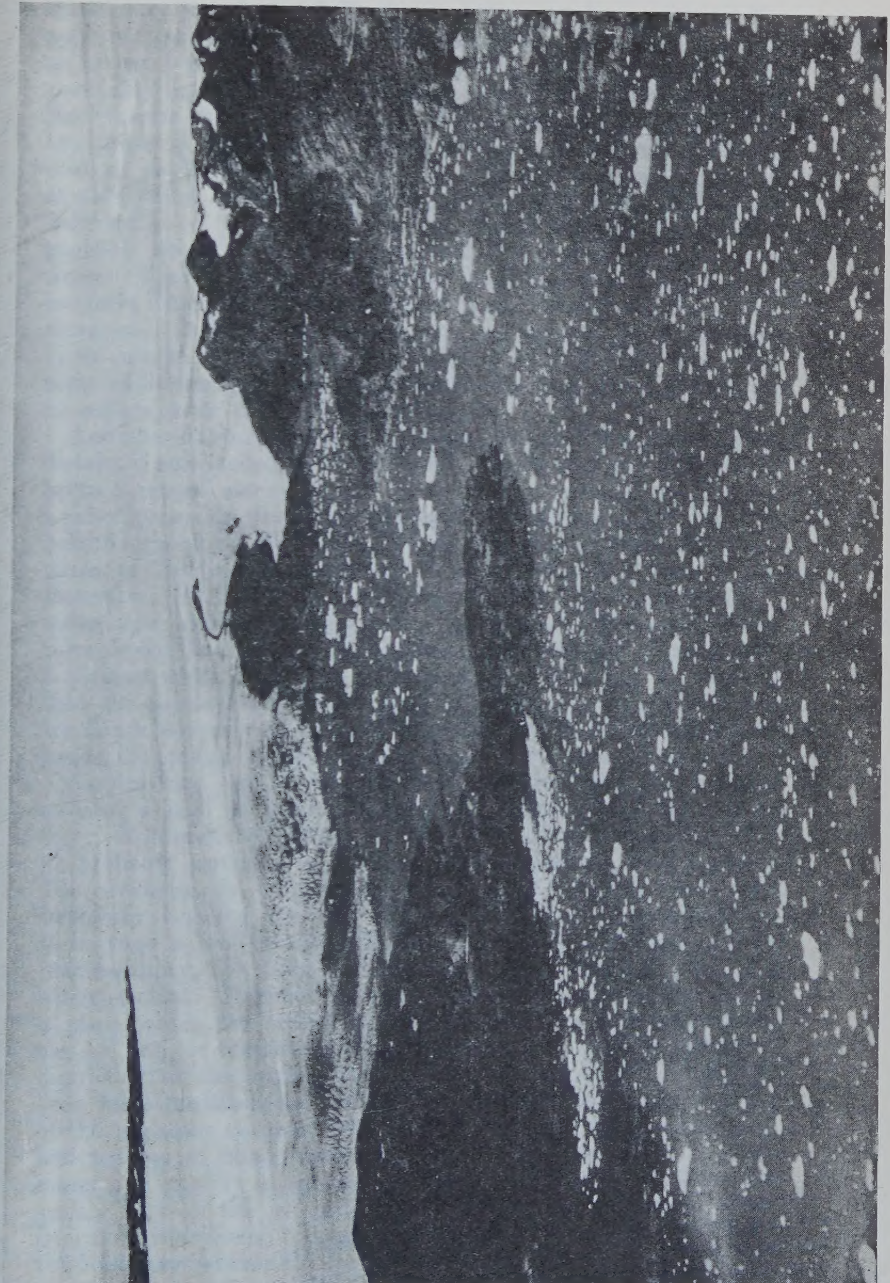
[1] A summary of Greenland stratigraphy with references will be found in "Stratigraphy of Greenland", by L. Koch, *Meddel om Grønland*, lxxiii, 209–315, 1929.



ICE CAP AND COASTAL MOUNTAINS, BASE FIORD

[*To face p.* 150.

Quaternary ice sheets of Europe and America have entirely disappeared makes reasonable the hypothesis that Greenland possessed an ice cap before the beginning of the Quaternary ice sheets. This possibility is strengthened by certain general considerations. Thus the Pliocene climate round the N. Atlantic where sediments of that age preserve an adequate record, seems to have been about as cold or colder than nowadays and the geographical factors of climate which would affect Greenland in particular, such as the distribution of land and sea in the North Atlantic region, were probably about the same as at present throughout Upper Tertiary times. Thus it might be expected that Greenland supported an ice sheet during Upper Tertiary time if the country had its present elevation. It is not my present purpose to attempt to evaluate or to enlarge upon these general lines of evidence, but to consider some additional evidence based on the development of land forms in certain parts of coastal Greenland.

A climber standing on any of the higher summits of the Angmagsalik district is surrounded by a panorama of mountain tops all reaching up to a general summit level. The mountains are clearly cut from a raised peneplain which slopes gently to the south and S.E. from the neighbourhood of Mt. Forel towards the coast. Near Mt. Forel much of the original peneplain is preserved as flat tops to the mountains (Pl. XII, Fig. 1). From here towards the coast spiky mountains gradually replace the flat-topped mountains, while towards the Ice Cap the flat-topped mountains tend to unite into a plateau which is but little dissected (Pl. XII, Fig. 2). In the field the conclusion is forced upon one that, here at any rate, the Ice Cap is covering an elevated peneplain which, at some distance inside its present margin, may be essentially unmodified.

Nansen long ago stated that he considered that the Ice Cap covered a land at least as dissected as Norway at the present day; Nordenskiold (1909), on the other hand, considered that it probably covered a plateau with occasional deep valleys. The evidence is conflicting. Maps of Greenland mark the boundary between the Ice Cap and the coastal mountains as if it were a well-established line, but actually, because of its inaccessibility, the boundary has rarely been seen and even less often studied. Expeditions on to the Ice Cap naturally choose a place where the ascent is gradual, and this is usually where the Ice Cap, or tongues from it, reach the sea. It is in just these districts that the original land surface may be expected to have been most modified, because of the steep fall of the ice, because of the nunataks rising above the ice which provide rock abrasive, and because of minor oscillations in the position of the Ice Cap margin. Certainly in these best-known, lower, marginal areas the surface form of the ice and its crevasses are an expression of an irregular underground topography as postulated by Nansen. Where the boundary between the Ice Cap and coastal mountains is high it is difficult of access. The Forel region could not be reached directly from the coast but only by a circuitous route, so that the final approach was from the Ice Cap side. It is such rarely-visited districts which provide the evidence that the Greenland ice sheet covers a high, little-dissected plateau. Thus photographs taken by Wordie's Expedition to Peterman Peak (Wordie and Whittard, 1930) show very clearly that there the mountains are still in an early stage of evolution from a plateau, and in this respect the district resembles the Forel area.

If the land surface covered by the higher parts of the Greenland ice sheet is an unmodified peneplain then this fact can be explained in two ways: either the uplift has been so recent that there has not been time for appreciable geological erosion or climatic conditions since uplift have been abnormal. An ice sheet covering a plateau and, therefore, unarmed with abrasive because no mountains project above the general level of the ice surface, would presumably act as a protection from the usual agents of erosion rather than as an agent of erosion itself; and the plateau might be expected to persist indefinitely. It is suggested that the higher parts of the rock surface of Greenland remain to-day essentially an unmodified peneplain, not because of very recent uplift, which seems improbable for reasons shortly to be given, but because of the continuous protection afforded by an ice sheet from the time of original uplift. That the lower marginal parts of the Ice Cap do not cover an unmodified peneplain probably implies the existence of warmer periods when the Ice Cap shrank in size and stream and river erosion began a marginal modification of the plateau, since continued by glacial erosion.

Trending south and then S.W. from Forel is a glacier which may be taken as typical of the unusual valley topography of the whole region. This glacier, between Forel and Flat Top (Pl. XII, Fig. 1), is about 3 miles wide; and the rock faces of Flat Top and the adjacent mountains, which are 10,000 feet high, fall at an even slope to the glacier which lies about 6,000 feet below their summits. Further down the glacier the same features are found, except that the glacier is between 5 and 10 miles wide and only 1,000 or 2,000 feet above sea-level. The mountains rising above this broad valley filled with glacier are those that preserve extensive remains of the original peneplain (Plate XII, Fig. 2). The topography, although simple, is remarkable. With respect to the agents of erosion the rocks are essentially uniform, and it is certain that the peculiarities of the topography are not due to bands of soft rock or tectonic factors. It is difficult to believe, as is usual for the regions of former Quaternary ice sheets, that the topography in this case owes its character only to a minor modification by ice of the forms developed during the normal course of river erosion. If this were to be assumed then, before slight modification by ice, there would have been a wide flat-bottomed valley with a meandering river cutting between high mountains preserving extensively an original peneplain surface, and this would be an unexpected association of mature and youthful forms. The topography of the Forel area must, I believe, be assumed to be mainly the result of glacial erosion at the margin of an ice sheet. The enormous amount of erosion accomplished in the valleys mentioned I would ascribe to prolonged rather than particularly intense action of the eroding agent, and the preservation of the peneplain on the tops of the mountains I would again ascribe to the protection afforded by an ice capping from the time of original uplift of the peneplain.

Whether regarded from the general point of view first dating or considered in the light of evidence afforded by the topography of the Forel group, it seems probable that the beginning of the Greenland ice sheet was contemporaneous with the main uplift of Greenland. Unfortunately only a rough approximation can at present be made of the time of uplift and this has to be based on a consideration of the sequence and relative length of such events as are known to have filled the gap in the sedimentary record between the Eocene and the Quaternary periods. The latest sediments, Cretaceous and Lower Eocene in age, occur only on the flanks of the Greenland shield. In West Greenland these sediments dip gently away from the centre of Greenland, showing a post-depositional uplift of Greenland. In East Greenland the Tertiary sediments are intimately related to extensive outpourings of basalts. The southernmost exposures of the basalts rest on thin sediments of presumed Tertiary age (Wager, 1932), and during the recent Danish Expedition of 1932 under Captain Ejnar Mikkelsen it has been possible to visit the Cape Dalton area of Lower Eocene sediments and to show that they lie at or near the top of the basalt series. The basalts and the rare associated sediments in East Greenland also dip away from the Ice Cap and therefore show a post Lower Eocene uplift of the country. Intrusive into the basalts and underlying Metamorphic Complex there are various extensive plutonic intrusions of ultrabasic and basic rocks, granites, syenites, and nepheline-syenites.[1] Though clearly belonging to the same cycle of igneous activity, these rocks presumably reached their present position after the main extrusion of the basalt lavas. Subsequently to the final solidification of the plutonic rocks there was extensive dike intrusion. The completion of the cycle of igneous activity may well have taken a considerable period of time, perhaps to the end of the Eocene. The present coastal mountains from Kangerdlugsuak northwards are cut from a peneplain rising in places at least to 8,000 feet, which is not parallel to the lava flows but cuts gently across these, and also across the plutonic intrusions and then on to the Metamorphic Complex. The lavas dip at an average of 10° seawards while the peneplain has a dip of only 3°. Subsequent to the plutonic intrusions and the dikes and yet before the final uplift of the part of Greenland here being considered, there was extensive peneplanation which reached down to the plutonic rocks, and this must have taken a long period of time.

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[1] Nepheline-syenites were not mentioned in an earlier paper (Wager, 1932) because of their possible association with minerals of economic importance.

Turning now to the events which succeeded the uplift, there is evidence on the one hand of the preservation of the raised peneplain and on the other of a vast amount of erosion. Since the preservation of the peneplain occurs side by side with unusually wide, flat-bottomed valleys, it cannot be considered due to very recent uplift, and certainly the development of the high mountains of alpine form near the coast points to the long continued erosion of the uplifted peneplain. Thus the spiky mountains between the coast and the flat-topped mountains in the Forel area rise to a height of 8,000 feet and are cut out of the tough gneisses of the Metamorphic Complex. The peneplain from which they are cut can be seen to be essentially continuous with that which, further north, passes from the basalts across the plutonic intrusions on to the Metamorphic Complex and presumably was uplifted at the same time. The broad glacier-filled valleys of the Forel group are also indicative of the enormous amount of erosion which has taken place, an amount which would be impressive whether it were considered to be due to the ordinary agents of erosion or to glacier erosion as here suggested. Deep and broad fiords such as Kangerdlugsuak and Kangerdlugsuatsiak have also a consequent relation to the uplifted peneplain and are believed to have been cut out since the uplift.

A consideration of this sequence of events during the Tertiary period, though giving no precise method of dating, nevertheless suggests sometime in the Miocene as the most probable age of the main uplift of Greenland. Both the general view and the analysis of the topography of the Forel region would suggest a similar, that is Miocene, date for the beginning of the Greenland Ice Cap. If this hypothesis can be further substantiated, it will give a new outlook in any attempt to explain the morphology of coastal Greenland.

SUMMARY AND ACKNOWLEDGMENTS.

Recent expeditions to Greenland enable a more accurate map, showing the form of the Greenland Ice Cap, to be prepared. The higher parts of the Ice Cap are now seen to be adjacent to the higher coastal mountains. Since Wegener has proved the isostatic depression of Greenland it is clear that the height of the Ice Cap is not, at its present stage, controlled by the form of the underlying surface. Apparently one of the factors in the control is the height of the coastal mountains which, where high, impede the outflow of the ice and cause it to pile up, forming the higher parts of the Ice Cap.

Since the Inland Ice of Greenland has persisted longer than the

Quaternary ice sheets it is reasonable to suppose that it may likewise have begun earlier. Where the Ice Cap is high it is probably overlying an unmodified elevated peneplain whose preservation is due to a continuous covering of ice since its original uplift. In the Forel area much of the original peneplain at a height of 10,000 feet is preserved side by side with low, broad, glacier-filled valleys. The anomaly of the association of what would normally be considered a young mountain topography with a mature valley system is believed to be due to prolonged glacial erosion on the margins of an ice sheet which has persisted ever since the uplift of the area and has therefore been the dominant or only factor in shaping the existing mountain and valley forms. There are no Tertiary sediments yet known in Greenland which are later than the Lower Eocene; and the main uplift of Greenland, estimated by considering such events as can be traced in Greenland in post Eocene time, is believed to be approximately Miocene in age. The Greenland Ice Cap, therefore, which seems to have originated contemporaneously with the main uplift, is believed to have been in existence since Miocene times.

I wish to express my gratitude to the late Mr. H. G. Watkins, the leader of the British Arctic Air-Route Expedition, for inviting me to act as geologist to the expedition and for the facilities which, during the expedition, he always granted me. I also wish to thank Captain Ejnar Mikkelsen and the Scoresby Sound Committee for providing me with another valuable opportunity for carrying out geological investigations in East Greenland during the Expedition of 1932 to the Blossville coast and Kangerdlugsuak. My thanks are also due to the Council of Reading University, who granted me leave of absence to take part in the former expedition, and to the Royal Society and the Trustees of the Cambridge University Worts Fund for grants for apparatus used in Greenland.

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EXPLANATION OF PLATES X–XII.

Plate X.

High Coastal Mountains immediately south of Kangerdlugsuak, East Greenland. The foreground mountains are 3,000 feet high; those near the horizon are about 8,000 feet and 60 miles distant from the coast. The gaps in distant mountains lead directly on to the unbroken Ice Cap. Air photograph by H. G. Watkins from 10,000 feet.

Plate XI.

The Ice Cap and Coastal Mountains, the Base Fjord, 30 miles west of Angmagsalik, East Greenland. The mountains on the right are 2,500 feet high and their rounded form is due to recent complete covering by the extended ice sheet. Where the belt of coastal mountains is relatively low, the Ice Cap extends over them and in places reaches the sea. The horizon can be seen as a white line near the top of the plate. Air photograph by H. G. Watkins from 10,000 feet.

Plate XII.

Fig. 1.—Panorama of mountains S.E. and S. of Mt. Forel. Flat Top, 10,000 feet, and some of the other mountains show the remains of the peneplain from which the mountains have been cut. The distant mountains are nearer the coast and are all spiky in form. On the right is seen the broad glacier 5–10 miles wide cutting between mountains 8,000–10,000 feet high. Photograph by A. Stephenson.

Fig. 2.—Panorama to the S. and S.W. from 10,500 feet on Mt. Forel. The glacier shown in Fig. 1 can be seen on the left. To the right of this, i.e. nearer the Ice Cap, the flat-topped mountains give place in a short distance to a high plateau which is but little dissected.

The Green Beds of South Knapdale.

By William J. McCallien, D.Sc., F.R.S.E., Glasgow University.

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3. The Green Beds.
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5. Barmore Island.
6. Structure.
7. Summary and Conclusions.

1. INTRODUCTION AND OBJECTS OF THE PAPER.

In his description [1] of the older rocks of Kintyre the writer has described in some detail the field characters of the Green Beds of that peninsula. Many difficulties were met with in the southern part of Kintyre where the rock-groups are repeated by folding. The chief of these difficulties were occasioned by the knowledge that schists identical in composition and appearance to the Green Beds occur at many different horizons below the Erins Quartzite.

It was therefore decided that, before the difficulties of mapping and interpretation could be removed, it was necessary to re-examine

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[1] *Trans. Roy. Soc. Edin.*, lvi, pt. ii, No. 17, 1929.

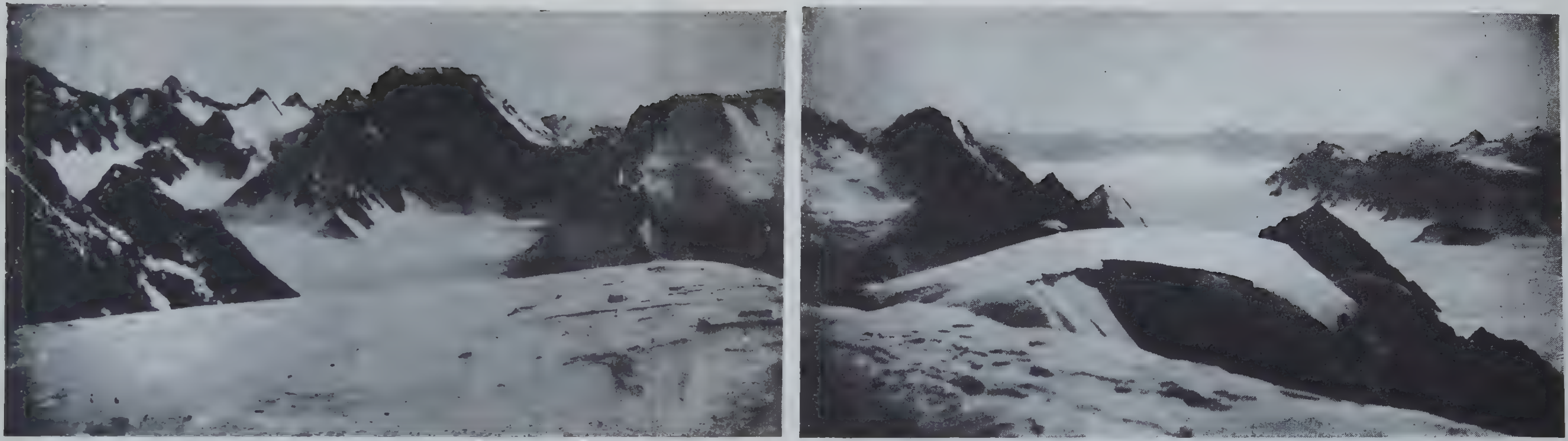

FIG. 1.—PANORAMA S.E. AND S. OF MT. FOREL.

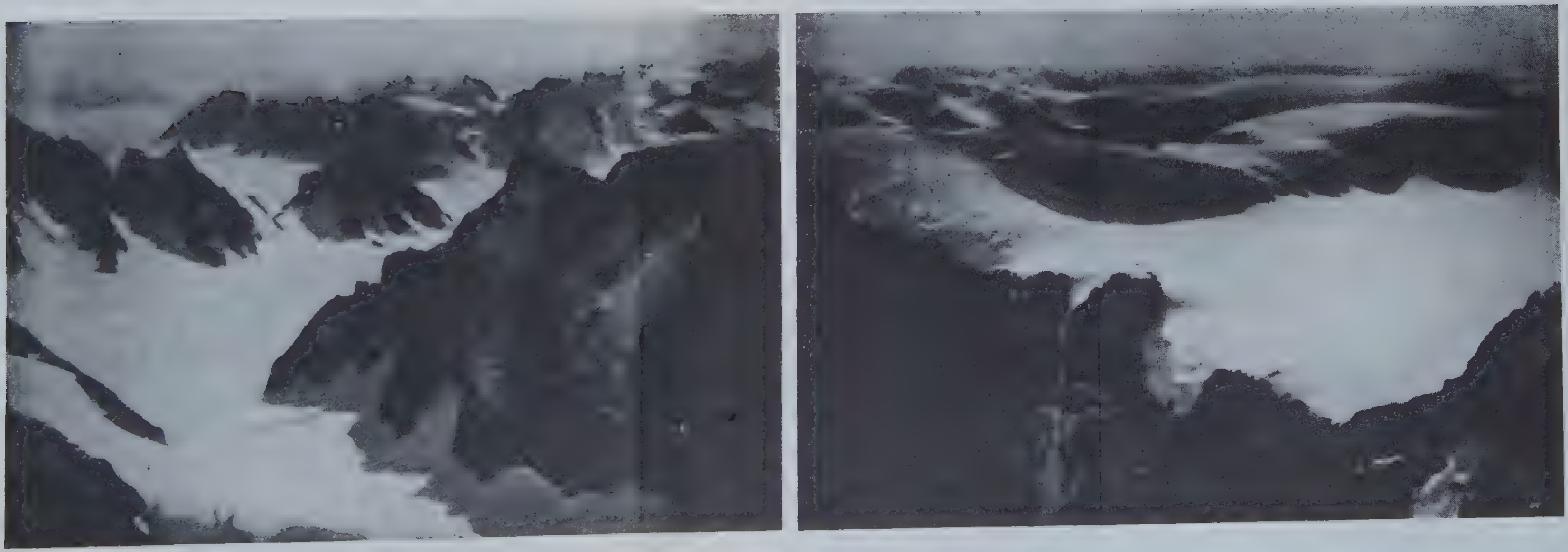

FIG. 2.—PANORAMA TO S. AND S.W. FROM MT. FOREL.

in greater detail the Loch Fyne section.[1] It is believed that in the light of this continued study of the type-section the task of re-examining Southern Kintyre will be considerably lightened. Already, in a traverse of Southern Kintyre since the publication of the work referred to above, many additional points of interest have been noted, and these were due in all cases to the increased capacity for recognizing Green Bed material not actually in the horizon of the Green Beds proper.

In the writer's previous work on South Knapdale[2] and in the *Memoir of the Geological Survey* on Jura, Knapdale, and North Kintyre, it was assumed that the Green Beds occur in a horizon some distance south-east of the Loch Tay Limestone. The schists between the two groups are called the Glen Sluan Schists. The object of the present paper is to show that instead of being able to restrict a narrow zone south-east of the Loch Tay Limestone as the horizon of the Green Beds it is more correct to say that Green Bed material occurs in the rocks from the north-western boundary of the Beinn Bheula Schists to the north-western margin of the Ben Lui Schists, and that green schists, of Green Bed type, are characteristic of that extended horizon. The writer has not attempted to map the bands recognized on the coast north-west of the Loch Tay Limestone in their continuation inland. They have been noted at many intervals in the hills north of Tarbert, on the shores of West Loch Tarbert, and in Antrim.

A large part of the area dealt with in the present note is included in the private grounds of Stonefield House and the writer desires to thank Captain G. Mackie Campbell for permission to use the grounds freely during field work (see Fig. 1).

The island of Barmore, north of Tarbert, is also included in the present description. On the 1-in. map, Sheet 29, and in the new $\frac{1}{4}$-in. map of the Glasgow district (Sheet 14) of the Geological Survey of Scotland, Barmore Island is indicated as Green Beds with a large sill of epidiorite. The rocks of the island strike north-west—south-east, at right-angles to those of the mainland. They do not, however, as will be shown later, belong to the Green Beds.

Recently Dr. F. C. Phillips[3] has published some interesting results of a microscopical examination of the Green Beds rocks from many different localities in the Highlands, and reference should be made to that work for a general description of the group. Phillips points out that a zone in which Green Beds occur abundantly, though with intercalations of other sediments, can be followed more or less continuously from Kintyre north-eastward to Glen Clova, in which direction they are thought to thin out. Towards the south-west the present writer has found the Green Beds in Antrim.[4]

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[1] *Trans. Geol. Soc. Glasgow*, xvii, pt. ii, 1924–5.

[2] *Trans. Geol. Soc. Glasgow*, xvii, pt. iii, 1925–6.

[3] *Min. Mag.*, xvii, No. 29, 1930, 239–256.

[4] GEOL. MAG., LXVIII, 1931, 126–133.

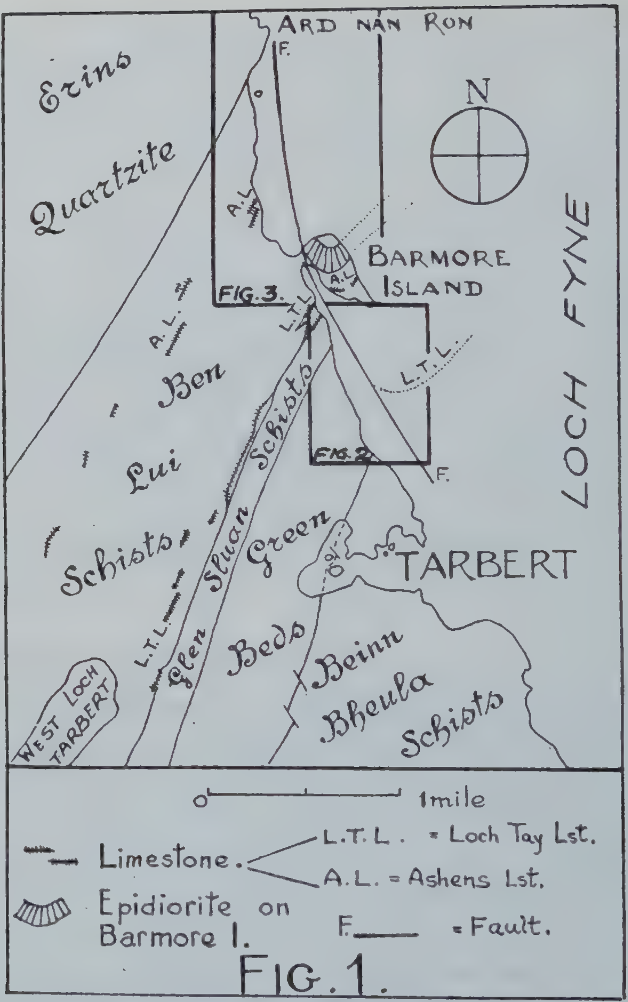

Fig. 1.—Index Map showing the main subdivisions of the Dalradian rocks around Tarbert and Stonefield, Loch Fyne.

2. General Subdivisions of the Dalradian Rocks.

The sequence of rock-groups in this part of South Knapdale is as follows, arranged from north-west at top to south-east at bottom.

Erins Quartzite.
Ben Lui (Stonefield) Schists ⎫
Loch Tay Limestone ⎪ Horizons with schists of
Glen Sluan Schists ⎪ Green Bed type.
Green Beds ⎭
Beinn Bheula Schists.

In Cowal, across Loch Fyne from the district at present under consideration, Clough recognized and mapped Green Beds well into the Ben Lui Schists.[1] On p. 89 of the Cowal Memoir Clough states: "Attention may be called to the wide range of the green beds. They occur here and there all the way from the north-west side of the Dunoon phyllites up into the Ardrishaig phyllites on Loch Fyne side. The character of these beds is so peculiar that it may with great probability be assumed that they all belong to one great formation. . . . The green beds therefore help to connect together the schists of the different areas, and their distribution renders it probable that the great mass of the schists belong to one great formation." In the Mid-Argyll Memoir J. B. Hill says (pp. 30 and 35) that in the Stralachlan area a well-marked Green Beds zone, over a mile in length, has been taken as the upper boundary of the garnetiferous mica-schist group along the eastern slope above Barnacarry, but in the neighbourhood of Mid Letter (south of Strachur Bay) Green Beds occur within the Ardrishaig group, whereas further north in the area north-east of Inverary Green Beds do not occur. Clough makes several references (*Cowal Memoir*, pp. 37 and 57) to the occurrence of Green Beds within the Ardrishaig Schists on either side of Mid Letter. Hill was of the opinion that in the Loch Awe group alone is the Green Beds phase of deposit unrepresented (*Mid-Argyll Memoir*, p. 60).

Professor Bailey[2] made use of the above facts in drawing the boundary between the Loch Awe Nappe and the Iltay Nappe in Cowal, believing, the writer thinks correctly, that the Green Beds are restricted to the Ben Lui Schists and do not cross into the Loch Awe Nappe. Although in the above statements Clough says Green Beds continue into the Ardrishaig Phyllites, Professor Bailey, on quite other grounds, has had to transfer some of Clough's Ardrishaig Phyllites to the Ben Lawers group. Professor Tilley on the grounds of metamorphism agrees with Bailey.

Green Beds were not shown on the 1 inch map Sheet 29 in South Knapdale, north of the Loch Tay Limestone, nor were they indicated by the Geological Survey in Sheets 12 and 20 in many parts of Kintyre at the horizon where they are usually so abundant.

3. THE GREEN BEDS.

The Green Beds are schists and grits of sedimentary origin, but they are of such unusual composition that they must have been derived almost directly from basic igneous rocks. There is, however, in this area at least, a gradual passage into more siliceous and micaceous rocks of a normal sedimentary type. Clough has drawn attention[1] to the resemblance between the Green Beds and the epidotic grits of the Torridonian. These Torridonian green grits have been derived from the disintegration of the epidotized surfaces of Lewisian Gneiss. The Green Beds often contain small oval masses of pale-coloured epidotic material such as, in other green schists, are supposed to represent metamorphosed vesicles.

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[1] *Mem. Geol. Surv. Scotland*, "The Geology of Cowal" and Sheet 29.

[2] "The Structure of the South-West Highlands of Scotland": *Q.J.G.S.*, lxxviii, pt. ii, 1922.

During their course from the Mull of Kintyre to Glen Clova the Green Beds pass gradually from the lower grades of metamorphism (determined in the pelitic beds) to the kyanite-sillimanite boundary. The Green Beds discussed in the present paper occur in the garnet zone. Garnets occur in the pelitic sediment around Tarbert harbour and northward of Tarbert into the Erins Quartzite. They are not abundant in the schists of the Green Beds type in this coastal section. Phillips says (p. 246 of the paper already mentioned): "The Green Beds are found within the garnet zone in the south-west near Loch Tarbert and Loch Fyne and pass again completely across the zone in Perthshire." The same author continues: "Hornblende now," i.e. in the garnet zone, "becomes abundant, usually with marked acicular habit, and only occasionally as platy crystals, which latter sometimes show zonary extinction." The occurrence of hornblende in the Green Beds of this part of Scotland is not common. According to J. B. Hill in the *Mid-Argyll Memoir* (p. 19), hornblende was not detected in the Green Beds of Cowal (cf. Clough, *Cowal Memoir*, p. 36). In Glen Fyne to the north-east of South Knapdale, where the metamorphism reaches a more advanced type, the Green Beds are converted into hornblende-schists almost identical to schists derived from the metamorphism of basic igneous rocks. In these hornblende-schists (Green Beds) the hornblende is authigenic, whereas according to J. B. Hill in the Memoir on Sheet 28, "hornblendic grains from the rocks near Tarbert are represented by small rather ill-defined crystals associated with irregular patches of chlorite and grains of epidote which probably mark allothigenic constituents" (p. 23). Hornblende has been seen by the writer in slices from the Stonefield coast, and from several districts in Kintyre. It is not common in the slides of Green Beds in the present collection, but it seems to be undoubtedly authigenic. On Tilley's metamorphic map of the South-West Highlands (*Quart. Journ. Geol. Soc.*, 1925, pl. ix) the Green Beds at Tarbert are completely within the zone of almandine, but south-east of Strachur they cross the garnet zone into the biotite zone. The north-western boundary of the biotite zone is there taken at a short distance south-east of the Loch Tay Limestone. Nevertheless, garnets occur in the Green Beds at the junction of the Cur and the Cab, south of Strachur (cf. *Mid-Argyll Memoir*, p. 20).

In the field the Green Beds are massive green schists and grits with fairly thin bedding compared with that of the grits above and below. The individual beds are on an average from 1 to 6 inches in thickness and grading from light siliceous coarser bases to dark greenish non-pebbly tops is met with. The grading in many cases is masked by later structures.

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[1] *Cowal Memoir*, p. 36. *Mid-Argyll Memoir*, p. 20.

Under the microscope the Green Beds of the South Knapdale and Kintyre region may be described as schists rich in albite, chlorite, epidote, with biotite in practically every case, and quartz in many slides. Garnet, altering to chlorite, and hornblende, are seen in only a few slides. The albites are similar to the albites of the more typical albite-schists, i.e. rounded water-clear grains and some angular crystals with numerous inclusions chiefly of magnetite and epidote, these being usually arranged parallel to an earlier foliation. Some of the water-clear felspars are of andesine. Phillips (p. 250) made a measurement of the felspar in material from localities around West Loch Tarbert and Loch Fyne, and found that it had a composition of $Ab_{95}\,An_5$ to $Ab_{90}\,An_{10}$. The biotite is usually interleaved with chlorite from which it has been derived. Many of the Green Beds are calcareous, the calcite in the slides reaching considerable amounts. This is especially true of the bands of chlorite-epidote-schists north-west of the Loch Tay Limestone, both on the mainland and on Barmore Island.

4. DETAILS OF THE GREEN BEDS OUTCROPS.

(*a*) *Beinn Bheula Schists.*

In the Memoir on Sheet 28 of the Geological Survey of Scotland it is stated (p. 21) that " near the top of the group and below the main Green Beds division, there are a few bands of Green Beds or of rocks allied to them. How far they represent infolds of the main division or oncomings of the same type of sedimentation on slightly different stratigraphical positions is uncertain, but the marginal zone in which they occur scarcely ever extends beyond half a mile from the boundary, and is usually within half that distance." It is mentioned that rocks of the Green Beds type have been noted about 200 yards west of Tarbert pier. The present writer has not seen these bands of Green Bed material in the Beinn Bheula group. No Green Beds have been recognized by the writer in the rocks of the present group on the South Knapdale coast which is described in this paper.

(*b*) *Green Beds Proper.*

On the coast (Fig. 3) these are first met with in the bay due west of Sgeir Port a' Ghuail and this belt stretches for 300 yards along the coast to a little beyond Carraig a' ghoib. Succeeding them to the north are about 230 yards of contorted siliceous and micaceous schists, with little admixture of Green Bed material. From Curraig an Staic northward for 330 yards is another band of massive Green Beds followed again at the headland on the northern side of Port nan Seilisdeir by siliceous and micaceous garnetiferous schists.

The Green Beds proper of South Knapdale are therefore composed of two bands of massive green schists of roughly 300 yards across, and separated from one another by a belt of normal siliceous and micaceous sediments.

Under the microscope these rocks are chlorite-epidote-albite-schists with biotite. Quartz varies considerably in amount and is absent from the most typical. In some of the very siliceous granulites of this group epidote is very abundant. Apatite is a common accessory mineral. One slice from the inland exposures at Tarbert has abundant garnet altering to chlorite, and a felspar more basic than albite (andesine or oligoclase-andesine). Two slices have been cut from a graded band about 3 inches in thickness—one from the top and one from the bottom. The top part is green in hand specimen and the bottom much lighter in colour and obviously siliceous. The latter under the microscope is a granulitic quartz-albite-schist with foliation defined by epidote grains and some biotite. There is abundant allothigenic plagioclase felspar with good albite twinning. In several cases these felspars are broken up into two or three fragments separated from one another by recrystallized quartz (Fig. 2). In the same slice there are porphyroblasts of secondary alkali-felspar with the inclusions typical of the albite in the albite-schists, and as a rule free from twinning. The slice from the top of the specimen differs markedly from the one just described and is

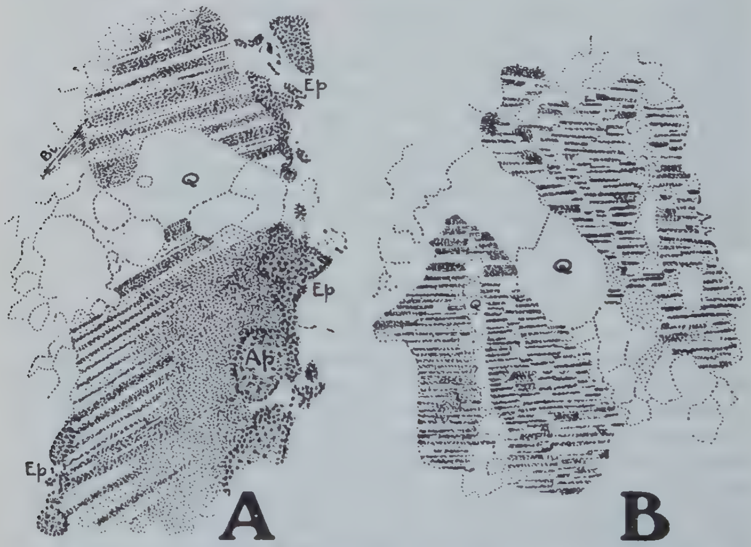

Fig. 2.—Clastic plagioclases in Green Bed from a few yards north of Curraig a'ghoib broken across by recrystallized quartz. Q = quartz; Ep. = epidote; Ap = apatite; and Bi = biotite, fine stippling with darker twin bands plagioclase (albite). × 90.

composed almost entirely of secondary albites (typical) and chlorite. Biotite is frequently developing from the chlorite. Compared with the other slice epidote is scarce.

(c) *Glen Sluan Schists.*

The schists of this group stretch for 500 yards from Port nan Seilisdeir to the coast due west of Sgeir na Douie (Fig. 3). In this

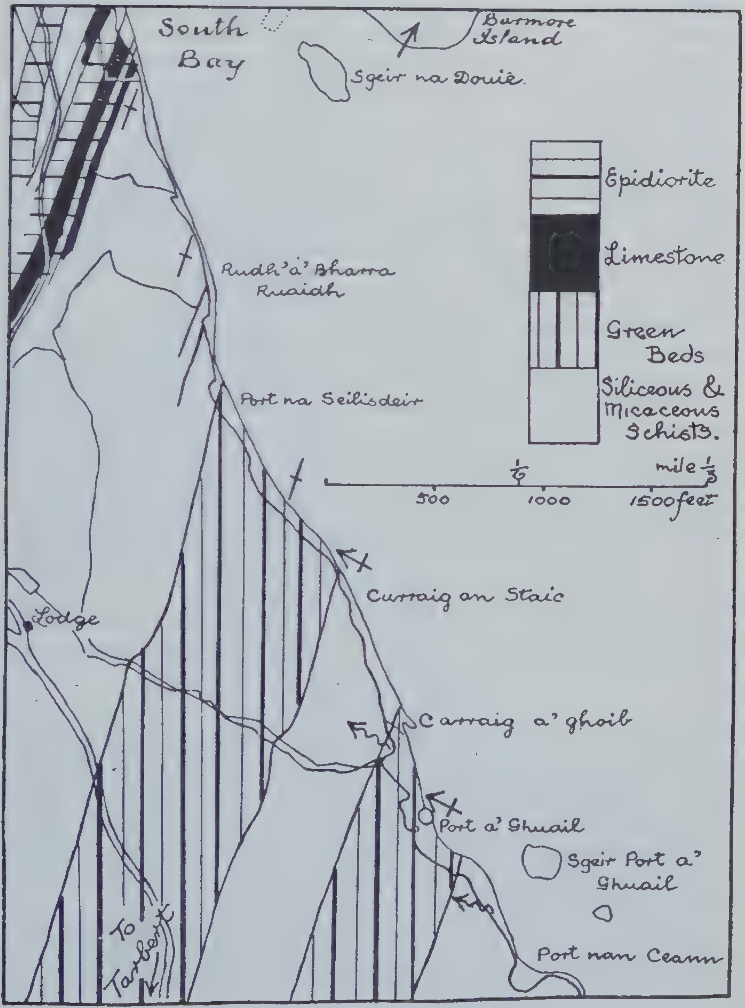

Fig. 3.—Sketch-map of the coast south of Barmore Island, Loch Fyne. The area of this diagram is indicated on Fig. 1.

stretch there are two bands of typical Green Beds at Rudh'a'Bharra Ruaidh, and some greenish stained schists at the fence 170 yards to the north. The Glen Sluan sediments stretch as far as the Loch Tay Limestone.

(*d*) *Ben Lui Schists.*

The outcrops of the Green Beds material in this group are best seen from the map (Fig. 4) of the Stonefield coast and of Barmore Island. The first outcrop north of the Loch Tay Limestone which the writer has seen, occurs at the small headland on the southern side of Port nam Paisd, 300 yards north of Stonefield House. The other outcrops to the north are indicated on the diagram. The largest and most important outcrop is that forming a marked headland 300 yards south of Eilean an Dunain. The rocks of this headland are as typically Green Beds as those at Port a' Ghuail. Except for thin green schists this is the last outcrop of undoubted Green Beds. Epidotic material may continue in the sediments as far as Ard nan Ron. There is a gradual passage from the Ben Luis to the Erins Quartzite. This fact was previously stated by the writer in 1924.[1] Elles and Tilley are of the same opinion.[2]

Under the microscope the Green Beds from the coast north of Barmore Island and from the island itself are typical of the group. A variant, however, is afforded by one slide from the headland 300 yards south of Eilean Dunain. In this many fairly thick bands are composed of muscovite and chlorite, and epidote grains are scattered regularly and abundantly through the whole. Large biotites, pleochroic from brown to green, are common and there are numerous pieces of apatite. In some of the chloritic Green Beds from this headland remarkably little biotite is developed, though the rocks are over 2 miles within the garnet zone. Nor has garnet been seen in the slices from this headland.

In one slice from the southern side of Port an Dunain hornblende is exceptionally abundant, and the rock is a hornblende-biotite-schist.

5. BARMORE ISLAND.

On Sheet 29 of the Geological Survey 1-inch map of Scotland Barmore Island is coloured as Green Beds with a large epidiorite sill in the northern part of the island. Its sediments, however, are predominantly mica-schists and grits with only subordinate outcrops of Green Bed type in the cliffs behind the sheepfold on the southern end of the island, and with several thin limestone beds, not hitherto recorded, a little farther north (Fig. 4).

These sediments afford an association met with in the main shore-section north of the Loch Tay Limestone but not to the south of it. Similarly in this shore-section epidiorite is only known with or to the

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[1] *Trans. Geol. Soc. Glasgow*, xvii, pt. ii, 1924–5.

[2] *Trans. Roy. Soc. Edinburgh*, lvi, pt. iii, No. 25, 1930.

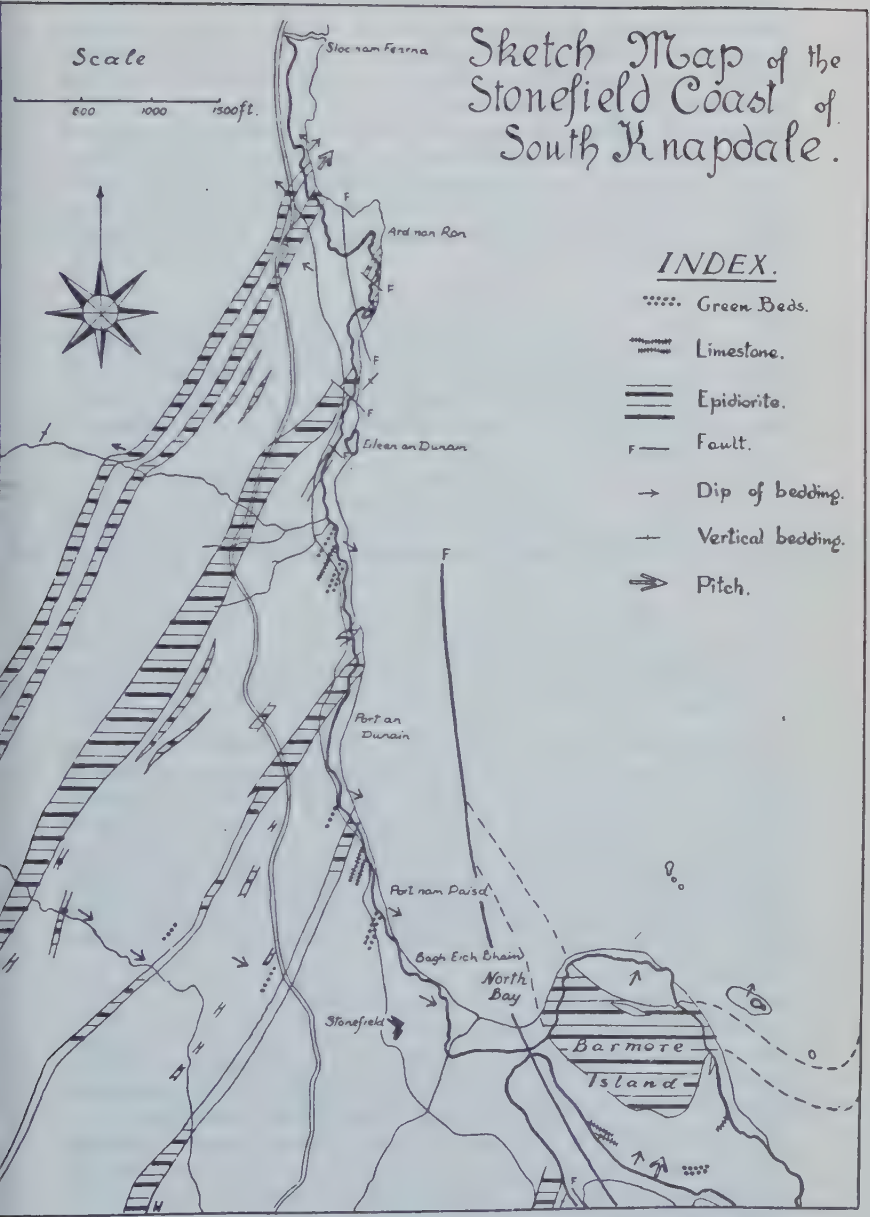

FIG. 4.—Sketch-map of the coast north of Barmore Island.

north of the Loch Tay Limestone. Thus the conclusion is irresistible that the Barmore Island rocks belong to the Ben Lui Schists. Probably the limestone beds correspond with the Ashens Limestone of the mainland (Figs. 1 and 4), which outcrops north of Port nam Paisd with Green Beds to the south.

The schists of Barmore Island dip to the north-east while those on the mainland dip to the south-east or are vertical. It has always been recognized that a fault intervenes. With the correlation given above it seems that this fault is a tear fault and that a southward displacement of the Barmore Island rocks has been responsible for the observed rotation of strike.

6. Structure.

The writer[1] has already dealt with the structure of South Knapdale, and has nothing new to add to what was stated in his previous works. Elles and Tilley,[2] however, have more recently drawn a section across this part of the South-West Highlands with a very different interpretation. The schists between Tarbert and Glenralloch[3] are shown by these authors dipping to the north-west at 30°, whereas they are vertical over most of the district, as has been recognized by all other workers. The rocks north of Glenralloch are shown with the same dip to the north-west, whereas they dip to the south-east for considerable distances. Fig. 5 gives a section across the Loch Fyne coast according to the present writer and accepted by those of his colleagues who have traversed the coast with him.

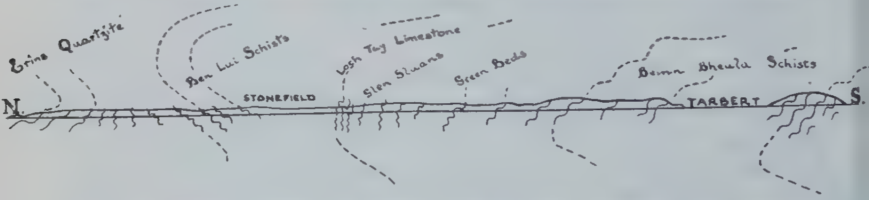

Fig. 5.—Section across the coastal region from Ard nan Ron through Stonefield and Tarbert to Mealdarroch Point. Length of section about 3 miles.

7. Summary and Conclusions.

(*a*) Rocks similar in appearance and composition to the schists of the horizon known as the Green Beds are shown to occur in South Knapdale from the north-western margin of the Beinn Bheula Schists to the south-eastern margin of the Erins Quartzite.

(*b*) Green Beds are not known by the writer to occur within the Beinn Bheula Schists of this part. Instead they commence suddenly with a thick band of massive Green Beds which is followed, after a short interval occupied by normal sediments, by another band of similar dimensions. The base of the Green Beds zone forms a well-defined boundary along a length of at least 50 miles in this part of Argyllshire, always keeping to the same stratigraphical position (cf. J. B. Hill, *Mid-Argyll Memoir*, pp. 60–1). From these massive bands towards the north the amount of Green Beds material becomes less in quantity until the Erins Quartzite is reached.

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[1] *Trans. Geol. Soc. Glasgow*, xvii, iii, 1925–6.

[2] Op. cit., fig. 2.

[3] On Fig. 1 Glenralloch runs between the head of West Loch Tarbert and the northern end of Barmore Island.

Further south in Kintyre Green Beds occur within the Beinn Bheulas, but they are always interpreted as infolds from the main zone to the north-west.

(*c*) This distribution could be explained if deposition of basic material began abruptly in large quantities at the end of Beinn Bheula times, and if the amount of basic material available as sediment decreased gradually towards the end of Ben Lui times. If such a conclusion is correct then the column on p. 158 shows the rocks arranged in order of age with the oldest at the bottom and the youngest at the top. On the other hand, the thinner bands to the north could be interpreted as representing the oncoming of the rather unusual type of deposition resulting in the Green Beds. Graded bedding in the Green Beds is not of very much aid in determining the original order of deposition. The writer has repeatedly searched the coastal sections for definite evidence as to relative ages. As has been previously mentioned, grading is fairly common, but occasional blanks render it useless. However, at this stage of the inquiry it appears as if the most southerly band were inverted—i.e. older than the underlying Beinn Bheulas. The grits overlying this Port a' Ghuail band, however, appear to be right way up, i.e. younger than the Green Beds. The writer does not feel convinced that the two bands of Green Beds represent the same one repeated by folding. Grading is also present in many bands of the Beinn Bheula group, but only at considerable distances from the Green Beds junction—e.g. on Mealdarroch Point—and with the existence of violent pre-Anticline folding no value is attached to it. Unfortunately the evidence is hardly sufficient to make a decision on the all-important question of the relative ages of these rocks.

(*d*) Barmore Island is described. The rocks of the island are chiefly gnarled micaceous schists and grits. These belong to the Ben Lui Schists and not to the Green Beds as believed by the Geological Survey.

(*e*) Thin limestones were discovered on the island by the writer, and these are correlated with the Ashens Limestone of the mainland. Green Beds occur on Barmore Island, as they do in the Ben Lui Schists, but only in subordinate amount.

The writer is indebted to Professor E. B. Bailey for company in the field, and for his constructive criticism of the original manuscript of this note.

Pollen Analyses of Fenland Peats at St. Germans, near King's Lynn.

By H. and M. E. Godwin, Botany School, Cambridge, with a report on the Geology by F. H. Edmunds.

Introduction.

THE Quaternary deposits of the Fenland, consisting of silts, clays. and peats, offer several problems of correlation. Large exposures of these beds have been rare, and hitherto no attempt at dating individual beds has been made, although from the descriptive point of view the whole of the Fenland deposits were dealt with very fully by Skertchley in 1877 (1).[1]

Recently, an excavation of an extent and depth seldom seen in the Fenlands was made at Wiggenhall St. Germans (now generally known as St. Germans), a small village about 4 miles south-south-west of King's Lynn, and situated on the left bank of the River Ouse ; the river at this point is strongly tidal.

A large drainage channel, the Middle Level, carries into the Ouse the drainage waters from an extensive area of Fenland in the neighbourhood of March. The outfall was originally controlled by a sluice, built in 1847, which, however, was undermined and broken away during a flood period in 1862 ; in 1874 a large sluice was built on another site. At the present time a scheme is being carried out by the Middle Level Commissioners to lower the level of the outfall so that drainage may be more expeditious and be independent of tidal movement. This scheme includes the construction of a new sluice and a pumping-station, which are being built near the site of the original sluice.

In the excavation for these works, a series of peats, silts, and clays was exposed, and to the peats a statistical microscopical examination has been applied, especially with respect to their content of pollen. This method has afforded on the Continent a valuable chronological index to post-Glacial peat deposits, but its application in the British Isles has been more limited, and its use has been practically confined to upland peat deposits.

Although the analysis of lowland peats presents certain features of difference from that of upland peats, yet it has been found to yield some evidence of the ages of these Fenland deposits, particularly of the lower beds, so giving an essential clue to our interpretation of all the post-Glacial history of the Fenland area.

The section was examined by Mr. F. H. Edmunds, of the Geological Survey, whose report was kindly placed at the author's disposal by the Director of the Geological Survey and Museum. The following account describing the section has been contributed by Mr. Edmunds.

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[1] Numbers in parentheses relate to References at the end of the paper.

DESCRIPTION OF SECTION.

Prior to the commencement of excavations for the foundations of the new Middle Level Sluice, the beds at the site, and on the area immediately surrounding it, were proved by a series of nearly thirty trial boreholes. These showed the Kimmeridge Clay surface to be, on an average, about 23 feet below Ordnance Datum Level; minor undulations occurred, which appear to be due to subaerial erosion prior to the formation of the Fen deposits now overlying the Kimmeridge Clay. A series of eight bore-holes in line, taken from the north-east to the south-west, showed a progressive drop in the Kimmeridge Clay surface from −22 feet O.D. to −25½ feet O.D.; about 100 feet south of the western end of the present works the Kimmeridge Clay surface was −30 feet O.D., and it was at this level about 300 yards north-east of the works.

The excavation covers an area approximately 300 by 100 feet in extent, and over the whole thickness of about 30 feet of alternating beds of clay, silt, and peat of Quaternary age was proved. Individual beds appeared to be continuous over the whole area, but unfortunately on account of engineering difficulties it was not possible to measure the complete section at any one spot. By means of measurements of partial sections and of records of the trial bore-holes, however, the following general section was recorded :—

HEIGHT OF SURFACE ABOVE LIVERPOOL ORDNANCE DATUM, 18 FT.

		Feet.
	Made ground	12
J	Blue clay	2
H	One-foot peat bed	1
G	Brown silty clay, passing into	3
F	Blue clay with *Scrobicularia piperata*	3
E	Two-foot peat bed	2
D	Blue clay, mottled brown in places, with *Cardium edule*	12
C	Six-inch peat bed, with oak-tree stools	½
B	Blue buttery clay. Locally a gravelly bed, with grey and brown sandstone pebbles, replacing the top foot of clay	6
A	One-inch peat bed	1/12
	Kimmeridge Clay surface	–

The Kimmeridge Clay was excavated to about 2 feet; it consisted of a grey and brown clay with traces of fossils and with broken septaria. The material was greatly weathered, and contained large numbers of rootlets from plants of the overlying bed.

The 1-inch peat bed (A) consisted of highly-decomposed black peaty matter on the surface of the Kimmeridge Clay, and represents vegetation existing prior to the formation of Fen deposits here. In all sections to the Kimmeridge Clay that were examined this bed was present with a general thickness of about an inch, but at times it was not more than a quarter of an inch thick, and its existence was indicated rather by the roots in the Kimmeridge Clay than by the peat bed.

The blue buttery clay (B) is a homogeneous unctuous clay in which no lines of bedding are apparent; their presence, however, is shown when a vertical face is dried; the clay contains a large percentage of water and on drying contracts considerably. Shrinkage cracks appear in a very regular pattern; horizontal cracks develop along parallel bedding planes not otherwise apparent, and vertical cracks form at fairly regular intervals.

At the top of this buttery clay a gravel-filled channel, about one foot deep, containing fragments of Septarian nodules and an occasional flint was observed, apparently running due east, immediately underlying the 6-inch peat bed (C).

The blue clay of bed D was less unctuous than that of bed B, and was on certain levels, particularly near the top, crowded with shells of *Cardium edule*. The clay of bed F was similar in texture, but contained *Scrobicularia piperata*, and passed gradually upwards into a more silty clay. At 5½ feet from the base of this bed was found the tibia of a deer, but it proves impossible to identify the species. Bed J generally resembles bed B.[1]

Peat beds (beds A, C, E, and H) are described in later sections of this paper.

The 12 feet of " made ground " is present, partly as the result of excavation of the Middle Level and its first sluice, and partly on account of deposition of mud dredged from time to time from the bed of the level.

An interesting case of landslip on a small scale was noted in the excavations (Fig. 1). At the eastern corner of the works the 2-foot peat bed (E), which generally was lying horizontally, was seen to dip to the south-east and to be duplicated; at the north-eastern corner these conditions were reversed, the bed dipping to the north-west.

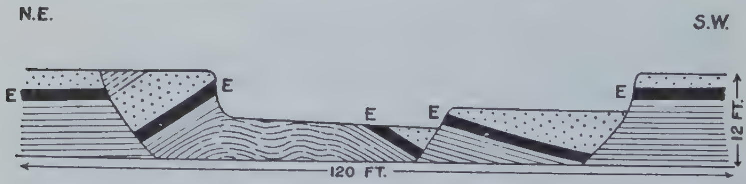

FIG. 1.—Diagram showing small landslips exposed in excavating for new sluice at St. Germans. E = 2-foot peat bed.

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[1] Comparative analyses of the Foraminifera of the clays and silts have been carried out by Dr. W. A. Macfadyen, and his results, and the conclusions drawn from them as to the conditions of deposition of the beds, are given in the succeeding paper in this journal. Dr. Macfadyen and the authors of this paper are members of the Fenland Research Committee, a body consisting of archaeologists, geologists, botanists, zoologists, and other scientists interested in the history of the Fenland basin and its deposits, and the present papers may be considered in some ways introductory to the investigations of the committee on the geological and palaeo-ecological side.

These dips were due to small landslips which may have occurred when the sluice was destroyed in 1862, the beds having slipped towards the Middle Level.

TECHNIQUE OF POLLEN ANALYSIS.

Small samples were collected in vertical series and at measured intervals from the clean-cut face of each of the peat beds ; a standard amount (about 2·5 ccs. by volume) of each was digested with 20 ccs. of 5 per cent KOH at 100° C. for twenty-four hours ; larger particles were strained off on muslin and the residue was centrifuged and washed three times with water ; finally, one drop of the residue was mixed with and mounted in two drops of safranin glycerine jelly.[1] The slides, when ringed with gold size, are permanent, the pollen is stained red and may be easily counted by the use of a mechanical stage. The pollen of the various tree genera is stated, following general European custom, as a percentage of the total tree-pollen ; *Corylus* pollen as a percentage of the total tree-pollen (in which it is not included). In Fig. 3, herbaceous and tree pollen, together with fern spores, are recorded as average number per traverse of the microscope slide.

The authors have followed the general practice of most Continental geologists and botanists who have investigated post-Glacial peat deposits, in dividing the post-Glacial into the climatic periods of Blytt and Sernander. Although the exact duration of these periods, Arctic, Sub-Arctic, Boreal, Atlantic, Sub-Boreal, and Sub-Atlantic, is not known, yet they are represented with great consistency and uniformity in peat-formations of all parts of Europe. The approximate correlations of the Blytt or Sernander climatic periods with other scales of post-Glacial time are given in the table below :—

Absolute Geochronology (De Geer).	Climatic Periods. (Blytt & Sernander).	Baltic Lake Periods. (Munthe).	Archaeological Periods.
2000 A.D.		Mya.	Historic Period.
1000 ,,	Sub-Atlantic (*moist and cold*).	Limnaea.	
0			Iron Age.
1000 B.C.	Sub-Boreal (*warm and dry*).		Bronze Age.
2000 ,,			Neolithic.
3000 ,,	Atlantic *warm and moist*).	Littorina.	(Kitchen-midden).
4000 ,,			
5000 ,,			
6000 ,,	Boreal (*warm and dry*).	Ancylus.	Mesolithic.
7000 ,,	Sub-Arctic.	Yoldia.	
8000 ,,			
9000 ,,	Arctic.		

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[1] The method has subsequently been made more closely quantitative.

One-inch Peat Bed (A).

This bed rested on and had roots penetrating into the weathered surface of the Kimmeridge Clay. It was so extremely poor in pollen that no statistical analysis could be made, but the following were present: *Alnus, Tilia, Pinus.*

The presence of *Alnus* is alone enough to date the bed as post-Boreal, and the occurrence of *Tilia*, even when the sample is so small as this, suggests that the bed closely resembles in age the peat bed C just above it, in which *Tilia* is very abundant.

Six-inch Peat Bed (C)

This bed is characterized by the abundant remains of fallen oak trees and of oak-tree stools still in the position of growth. The fallen trunks were much compressed, measurements varying from 4 or 8 inches across on the widest axis, though some trunks were over 30 feet long. All the trunks were lying in the same general east-to-west direction, and the root systems were confined to the peat layer, not turning down into the clay below, a fact suggesting tree growth under marsh conditions with the water table very close to the ground surface. A vertical series of three samples, A_2, A_3, and A_4, approximately 1 inch apart, was taken in one site, and in another sample (D_2) was taken immediately below the fallen trunk of an oak, and D_1 immediately above it. In the pollen diagram of Fig. 2, the analyses of A_2, A_3, and A_4, have been set on a fixed vertical scale, and D_1 and D_2 have been subsequently inserted in positions indicated by their pollen content.

The pollen diagram shows three features of primary interest. Perhaps the most obvious feature of the pollen diagram is the extraordinarily important rôle played by oak and alder pollen, and the complete change over in dominance from alder to oak throughout the bed. The authors believe that this is the expression of a local Fen succession from alder carr to oak-wood, such as may still be seen, though in fragmentary form, in parts of the Norfolk Broads at the present day (2). This view, which is applied much more fully for the next succeeding peat bed, is supported also in this case by changes in the relative amounts of non-tree pollen and fern spores, which were also counted though not shown in the figure.

The general composition and drift of the pollen spectra afford rather scanty evidence of age, except that the assemblage is clearly a post-Boreal one, and there are, especially in the basal layers, extremely high percentages of lime pollen (15·5 and 16 per cent). Values of this magnitude have, we believe, not been recorded before in this country, but this may well be due to the focussing of attention hitherto upon upland peat-bogs. It seems certain from preliminary observation that similar or even higher percentages of *Tilia* occur in other lowland coastal and Fen deposits of Eastern England, and the lime may well have been limited, as an important component of the mixed oak-woods, either to lowland areas supporting "Niedermoor" rather than "Hochmoor", or to the eastern part of this country. Although comparison within this country is not possible, Overbeck and Schmitz in their recent work on the history of post-Glacial vegetation in North-West Germany (4) give a "*Tilia* phase" as a recognizable and constant occurrence over the greater part of the territory in question. It follows the Pine-Hazel period, and is succeeded by the Oak-Hazel Period, and it is to be regarded as being of Atlantic age. West of the River Weser, the *Tilia* phase is short and the percentage values are often very high (up to 25 per cent), whereas east of the Weser the phase shows lower values (up to 7 per cent), and is of longer duration, extending into later Atlantic times. It seems very probable that the St. Germans peat beds A and C correspond with this *Tilia* phase, and it is interesting to note that peat samples dredged from the mouth of the River Weser and the Jade at Wilhelmshaven, at a depth of 10 to 15 m. below mean sea-level, evidently belong to this phase equally with the St. Germans beds about 5 to 7 m. below sea-level on the English coast.

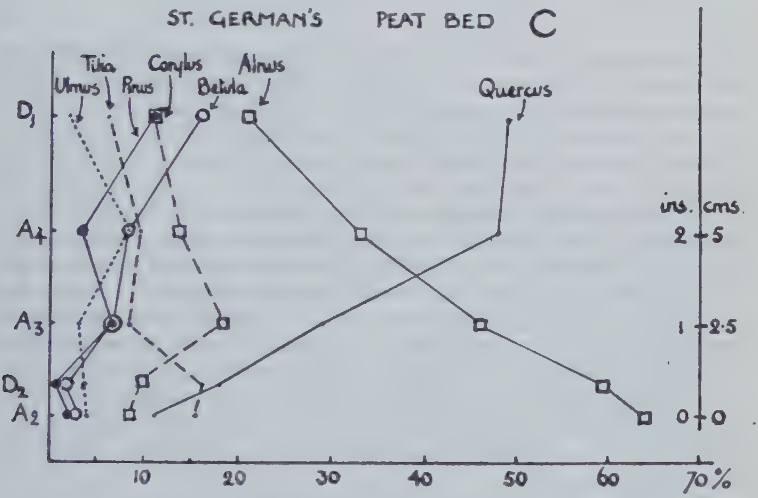

FIG. 2.—Along the horizontal axis the pollen frequencies are given as percentages of the total tree pollen: *Ulmus* (Elm), *Tilia* (Lime), *Pinus* (Pine), *Betula* (Birch), *Alnus* (Alder), and *Quercus* (Oak). *Corylus* (Hazel) is expressed as a percentage of the total tree pollen though not reckoned in it.

Peat samples dredged further seawards from the two coasts and in deeper water show in both cases pollen spectra indicative of greater age. Thus Erdtman gives analyses from the Jade-Weser district, some of which include either only *Pinus* and *Betula* (*Be.* 73 per cent, *Pi.* 27 per cent), whilst others, though including *Corylus*, still have no

Alnus in them. Similarly, the present authors have analysed moorlog dredged from the Leman and Ower Banks off the North Norfolk coast, and found the following pollen spectra :—

Betula.	*Pinus.*	*Quercus.*	*Corylus.*
16	67	17	80
13	85	14	81

This corresponds closely with Erdtman's analysis of samples from the same site and confirms the Boreal age of the peat, though this was already strongly suggested by the discovery of a Maglemose type of bone harpoon embedded in peat dredged from these banks (7).

Pollen analyses from still deeper and more remote parts of the North Sea have given large numbers of early Boreal spectra (5), and the conclusion would seem justified that during the formation of the North Sea at the end of the Boreal period progressive transgression of the sea submerged peat deposits of successively younger age, working from the deepest central portions outwards. Thus, the lower peat beds of St. Germans would appear to mark only a phase in this transgression, which involved the formation of blue marine or brackish-water clays over the whole of the area now occupied by Fenlands behind the Wash. It is a remarkable fact that over some areas of the North Sea bed the Boreal peat beds appear to have no silty covering, although thick deposits overlie the newer coastal beds.

The last important conclusion deducible from the pollen diagram is the complete absence of any break in the pollen series between samples D_2 and D_1, taken respectively just below and just above one of the prone oak trunks of the bed. It would appear that conditions were much the same after the tree fell as when it was growing : no catastrophe seems to have occasioned the wholesale destruction of an oak-wood, such as flooding by salt water, or invasion by *Sphagna*, causes very frequently invoked to explain fossil forests in post-Glacial and earlier peats, but the trees seem to have grown, fallen, and become embedded in the peat throughout the normal development of the oak-wood. It is probably only the present infrequency of oak-wood as a later stage of vegetational succession in lowland marshes, which has led to the creation of " catastrophic " hypotheses.

Two-foot Peat Bed (*E*).

This peat bed, separated from (C) by marine clay, was brown amorphous marsh peat throughout, containing small pieces of wood rather infrequently, and not at all in the upper 6 inches, where abundant remains of the reed *Phragmites* were recognizable.

In Fig. 3 are given the results of pollen analysis of a vertical series of eight samples passing through the bed in one place, but of these, the three upper showed so little tree-pollen that it has not been graphically recorded, though other spores have. The tree-pollen content of B_8, B_9, and B_{10}, was not evidently different in composition from that of the lower samples.

There is little or nothing in the tree-pollen spectra to permit dating, though it is to be noted that *Tilia* is now completely absent. After the early phase in which the pollen of *Quercus* and *Alnus* are present in roughly equal amounts, the *Quercus* rises to an extraordinarily high value (86 per cent), the *Alnus* falling correspondingly, and with it the other trees. The view that this change is due to a local vegetational succession is strongly supported by the diagram for herbaceous pollen, salicoid pollen, and fern spores. The results are given in absolute amounts (as pollen grains per unit area of slide surface), but similar results are obtained, though less conveniently graphed, if the frequencies are stated as a percentage of the total tree-pollen.

Both B_3 and B_4 are marked by considerable amounts of a pollen-grain referable either to the *Chenopodiaceae* or to the *Alsineae* (*Caryophyllaceae*): B_5, B_6, B_7, and B_8 show these grains disappearing completely. On account of the very marked preponderance in European salt-marshes of plants belonging to the families *Chenopodiaceae* and *Alsineae* (e.g. *Salicornia* sp., *Suaeda maritima*, *S. fruticosa*, *Obione portulacoides*, *Spergularia marginata*, etc.), the presence of this grain in abundance has been held by Overbeck and Schmitz (4) to indicate salt-marsh conditions, a suggestion backed in their case, as in this, by its prevalence in basal peats immediately over marine or brackish-water deposits. The sequence of non-tree spores available here enables us, however, to carry the interpretation of Overbeck and Schmitz much deeper. In B_4, pollen of *Compositae* and *Gramineae* reach strong maxima which suggest other and possibly later phases of salt-marsh succession with especially *Aster tripolium*, *Glyceria maritima*, and *Festuca rubra*. In B_5, salicoid grains (almost entirely small and probably referable to *Salix* itself) have become suddenly three times as numerous as all the tree-pollen put together, a fact suggesting replacement over wide areas of the salt-marsh by scrub dominated by willows, i.e. " carr ". The simultaneous maximum of fern spores recalls the extensive fern undergrowth of the early stages of *Rhamnetum* (buckthorn) carr in Wicken Fen, and of alder-willow carr on the Norfolk Broads. In B_6, the Filicales maximum has vanished, and the salicoid value, though still high, contains a fairly large percentage of much larger grains probably referable to *Fraxinus*. The two facts together possibly suggest invasion by ash and corresponding degree of dryness or shade inimical to fern growth. The next sample, B_7, apparently shows the culmination of the succession in oak-woodland, for the total absolute amount of tree-pollen has increased enormously and practically all of it is *Quercus*. The pollen of the carr bushes (willow and alder) and of the ash have almost disappeared, though some temporary phase

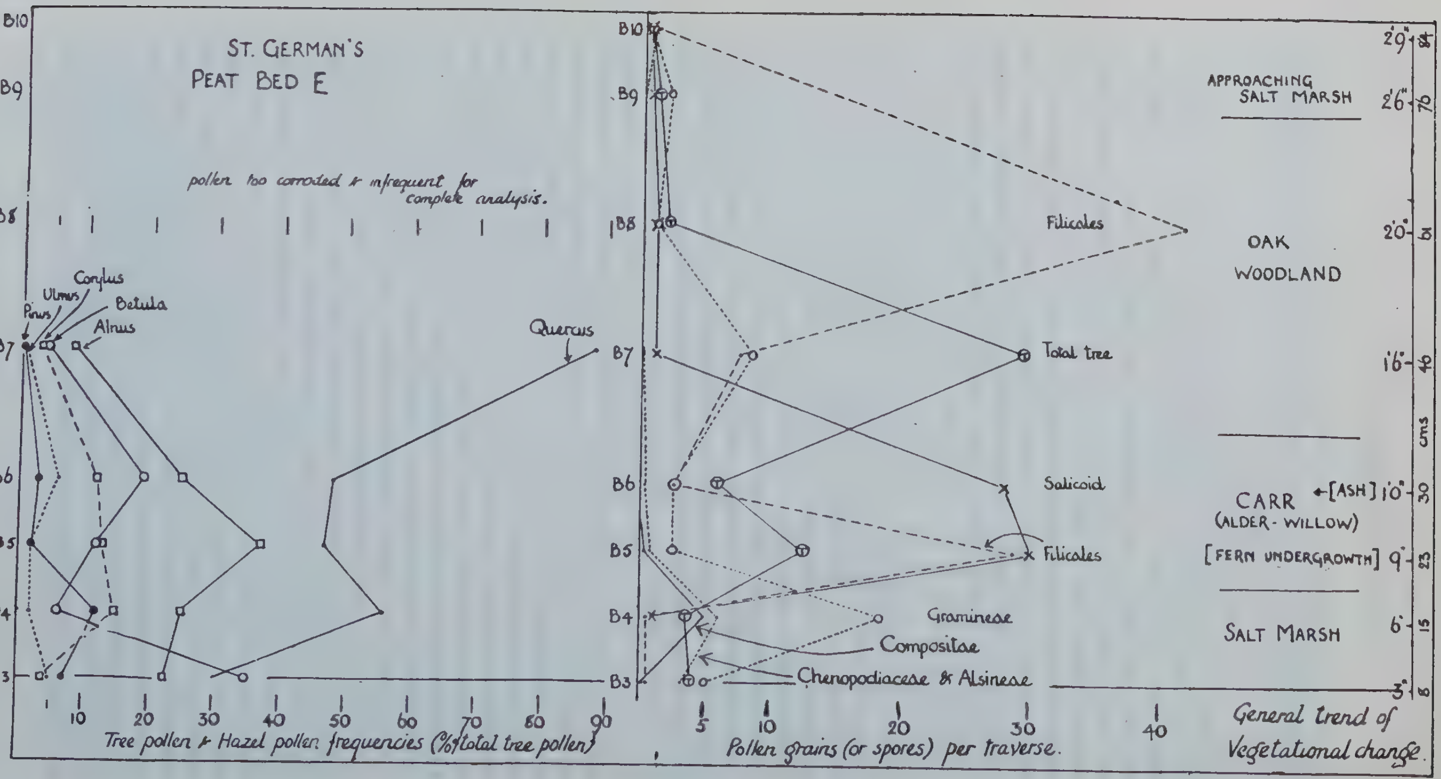
ST. GERMAN'S
PEAT BED E
pollen too corroded & infrequent for complete analysis.
B10
B9
B8
B7
B6
B5
B4
B3
Pinus
Ulmus
Corylus
Betula
Alnus
Quercus
10
20
30
40
50
60
70
80
90
Tree pollen & Hazel pollen frequencies (% total tree pollen)
Filicales
Total tree
Salicoid
Filicales
Gramineae
Compositae
Chenopodiaceae & Alsineae
5
10
20
30
40
Pollen grains (or spores) per traverse.
APPROACHING SALT MARSH
OAK WOODLAND
CARR (ALDER - WILLOW)
←[ASH]
[FERN UNDERGROWTH]
SALT MARSH
General trend of Vegetational change.
29"
26"
20"
16"
10"
9"
6"
3"
84
76
61
46
cms
30
23
15
8

FIG. 3.

of grass undergrowth (? *Phragmites*) is suggested by the higher grass-pollen value. Fern spores become more abundant, rising to extremely high values in the next sample, B_8 (over fifty times as abundant as the total tree-pollen). The presence of abundant fern sporangia as well as spores indicates that the ferns were growing here *in situ*, and were presumably under shelter of woody plants. Throughout B_8 and B_9 pollen preservation is extremely poor, but *Quercus* still dominates the tree-pollen, and there is little salicoid pollen, so that it may be presumed that oak-wood still covered the area during the formation of B_8 and B_9, but that conditions were so unfavourable for pollen preservation that tree-pollen was mostly destroyed, whilst the thick-walled fern spores, being much more resistant, were more abundantly preserved. It seems very probable that the increasing consolidation, raising, and drying out of the ground-surface under oak-wood might give rise to just these conditions. In B_{10}, all pollen has fallen to very low values save that of the *Chenopodiaceae-Alsineae* type, which is increasing again, an index of salt-marsh conditions and of the recurrence of marine transgression with deposition of further beds of blue clay. The degeneration of oak-wood to salt-marsh was marked in the Macro-remains by the abundance of *Phragmites*, indicative of the wet freshwater or brackish-water conditions preceding the actual salt-marsh formation.

The story of vegetational succession above outlined has been shown diagrammatically in Fig. 3. It is not to be thought that the succession necessarily took place all on this actual site : it may very well have done so, but the early salt-marsh pollen is probably the record in freshwater peat of extensive salt-marshes in the neighbourhood ; the tree-pollen maximum, as we have said, probably did represent oak-wood on this actual site. The vegetational history deduced from the micro-fossils is certainly one which does not conflict in any way with the sequence of vegetational phenomena observable in suitable marshlands of England and North Germany at the present day.

The recognition of the local successions as controlling pollen composition is of extreme importance, since it is quite clear that the great changes in the percentages of alder and oak-pollen are edaphically determined, and are quite unrelated to climatic change. Similar influences may be controlling the relative amounts of pollen of *Betula*, *Corylus*, *Ulmus*, and *Pinus*, though the relative constancy of these suggests pollen wind-borne from neighbouring uplands. The whole system of pollen-analysis is based upon climatic control producing effects upon tree growth and forest composition comparable all over a country or a continent, and so far, especially with upland peats, the principle has broadly held. It doubtless will continue to hold, but evidently in the interpretation of the results of the micro-analysis of lowland peat considerable stress must be placed also on the influence of local edaphic circumstances (i.e. soil or ground factors), especially in relation to phases of successional change.

One-foot Peat Bed (H).

The pollen analyses of this peat bed are derived from three samples at the top and bottom and middle of the bed; they are shown in Fig. 4. They afford only slender evidence for dating purposes, though the single beech grain found in E_1, and the persistent values of 10 per cent or more of *Pinus* suggest Sub-Boreal or Sub-Atlantic age (8). The total absence of *Ulmus* is rather striking: the significance of this will probably become apparent only when more detailed comparison is possible throughout the neighbourhood.

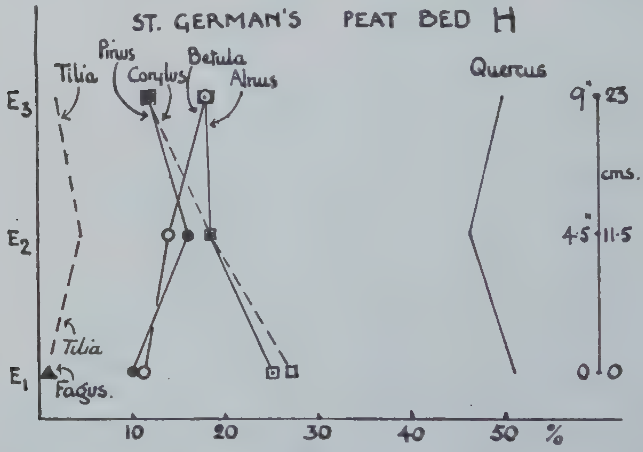

FIG. 4.

The micro-fossils, other than tree-pollen, show some evidence of local Fen succession throughout the bed, but conditions were here clearly much more uniform than through the formation of bed B.

ARCHAEOLOGICAL AND GENERAL CORRELATIONS.

In May, 1932, one of the workmen employed in the excavation reported the discovery in the upper 2 or 3 inches of the 2-foot peat bed (E) of some glass beads. Although digging was suspended at once and carefully recontinued afterwards in the presence of the authors no more beads were found, so that the evidence of discovery rests solely on the testimony of the workmen. It is further to be noted that very close to the site where the beads were found much disturbance had taken place, possibly connected with building or breaking-up of the first sluice, although the peat bed was locally intact, and it was difficult to see how such disturbance could have introduced the beads into the peat bed once it had been formed.

The beads have been examined, by the kindness of Mr. Horace C. Beck, and prove unfortunately very difficult to date. The beads have now been given by courtesy of the Middle Level Commissioners, to the Cambridge Museum of Archaeology and Ethnology, and

Mr. Beck's detailed report is given as an appendix to this paper. The report concludes that "there are two periods when beads similar to Nos. 1 to 6 were made. One is La Tène, which in this country might extend up to 50 B.C. or even later; the other is Saxon".

In view of the unsatisfactory conditions of the find, however, even this broad dating must not be too readily applied to the peat bed E itself.

The dating which has been suggested for the other peat beds on a basis of pollen-content is necessarily tentative at this stage, and it it not proposed to attempt here any kind of correlation of the St. Germans beds with neighbouring coastal or inland deposits of peat. Such correlation and closer dating must await much fuller investigation of sites distributed over the whole area. There seems a general probability that the two basal beds really are of Atlantic age, though it is quite possible that the *Tilia* maximum in this country, and in North-West Germany, were not exactly contemporaneous.

CONCLUSION AND SUMMARY.

1. The beds of peat and clay overlying Kimmeridge Clay at St. Germans are all post-Glacial deposits, and their content of tree-pollen indicates that they are all post-Boreal in age.

2. The two lower peat beds, one a thin peat (A) on the Kimmeridge clay surface itself, and the other a forest bed 6 inches thick (C) and 6 feet above the first, both show high percentage frequencies of *Tilia* pollen, and may be correlated with peat beds of similar pollen-content occurring off the north-west coast of Germany at about the same depth below sea-level. This correlation suggests Atlantic age for the basal deposits.

3. Peats of Boreal age are found at greater depths below sea-level off the Norfolk coast and over the North Sea as a whole, and marine or brackish-water clays overlie the two lower peat beds, and similar deposits extend far inland through the Fens.

4. The 2-foot (E) and 1-foot (H) peat beds afford in their pollen-content little evidence as to precise age, except that the upper has a rather high content of *Pinus* and a single beech grain which, perhaps, indicates Sub-Boreal or Sub-Atlantic Age.

A description has been given of a discovery in the 2-foot peat bed (E) of glass beads attributable to the Roman or Saxon period, but the conditions of the discovery do not permit great weight being given to this as a means of dating the bed.

5. A vertical series of samples through the 2-foot peat bed (E) shows successive maxima in the frequency of the micro-fossils, as follows: *Chenopodiaceae* and *Alsineae*, *Compositae*, and grasses—ferns—*Alnus* and salicoid grains—*Quercus*—ferns—grasses—*Chenopodiaceae* and *Alsineae*. This is interpreted as indicating a vegetational succession from salt-marsh *via* brackish-water and willow-alder carr, to oak-wood, and subsequent retrogression *via* salt-marsh to marine or brackish-water conditions again.

6. Similar successional changes are proposed to explain the change-over from early *Alnus* pollen maximum to a later *Quercus* pollen maximum in the 6-inch peat bed (C), and the changes in non-tree pollen and fern spores in the upper (1-foot) peat bed (H).

7. The foregoing results suggest that in the interpretation of the results of pollen analyses for lowland peats considerable allowances must be made for edaphic influences, and especially for vegetational succession, before correlation can be attempted on the basis of climatic control of tree-pollen frequency.

The authors would like to express their indebtedness to Major G. Fowler (Vice-President of the Fenland Research Committee) for drawing their attention to the existence of the excavation and for much subsequent assistance; to Mr. D. Hill, the resident engineer, for his courtesy and help in facilitation, observation, and collection of samples; to Mr. Beck, for giving his expert opinion and report on the beads; and to Dr. K. Blackburn, for her helpful advice on the technique of pollen analysis.

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APPENDIX.

Note on the Beads found embedded in the top of the Two-foot Peat-bed (E) at St. Germans, near King's Lynn.

By Horace C. Beck.

Seven beads were found, details of which are given below :—

Bead No. 1.—Pale cobalt-coloured annular glass bead. Weight, 5·21 g.; sp. gr., 2·412. There are two varieties of this bead which are very similar: one is of the La Tène period, and the other is Saxon.

There has been a small difference of specific gravity in practically all the specimens I have examined, but it is so slight that I do not think it is safe to trust as a means of dating them. At the same time it has been fairly consistent, as in twelve specimens from different sites dated to the early period in Britain, France, and the Mediterranean the specific gravity has been below 2·46, and the only other early specimen I have tested was 2·485. On the other hand, all the beads that I have tested which I *know* to be Saxon have a specific gravity of 2·485 or over. I have, however, recently seen a bead from Lincolnshire with the same specific gravity as this No. 1, which, I think, is probably Saxon. Blue annular Saxon beads of this type, but usually smaller, are more common in the eastern counties than in any other part of England.

Bead No. 2.—Pale-green glass bead. Weight, 3·739 g.; sp. gr., 2·447. I have seen two beads very similar to this one; one is from a Saxon cemetery at Faversham (sp. gr., 2·401), and the other from Kingsdown Camp and is supposed to be Pre-Roman (sp. gr., 2·44).

Bead No. 3.—Pale amber-coloured annular glass bead. Weight, 3·975 g.; sp. gr., 2·438. A bead identical with this comes from Lakenheath, but unfortunately it is not dated. A bead of similar type, but smaller, is from the Saxon cemetery at Faversham (sp. gr., 2·531), and another is from Rhodes; the first is Saxon and the second almost certainly La Tène.

Bead No. 4.—Pale-bluish annular glass bead. Weight, 3·213 g.; sp. gr., 2·452. This pale-blue glass has a very clear colour, which is probably due to copper. Such glass is found extensively in the Mediterranean area. In some cases it is found as early as 500 B.C. A bead very similar to this, but rather smaller and of slightly deeper colour, comes from Damascus. It is made in the same manner, has a sp. gr. of 2·488, and is supposed to date from before the Roman period.

Bead No. 5.—Pale-green annular glass bead. Weight, 2·806 g.; sp. gr., 2·375. The lower specific gravity of this bead is due to the large number of air-bubbles included in it.

Bead No. 6.—Pale-green glass annular bead. Weight, 4·604 g.; sp. gr., 2·375. There is a helical line on the end of this bead, which is very similar to that of some of the Saxon beads.

Bead No. 7.—Spherical bead with spiral lines round it. Weight, 3·275 g.; sp. gr., 2·456. I cannot recollect having seen a bead like this. It is not at all suggestive of Saxon work. The base is made of a dirty greenish-white glass. The red glass is a copper glass, in which the particles of copper are in the form of pure metal. The nearest approaches to this bead that I have seen amongst Saxon specimens are some small bi-cone beads with a zone band round them, this band consisting of a red stripe in between two white ones. Beads made by putting strips of variegated canes round a more or less colourless core were made in Italy at a fairly early period, but these do not resemble this No. 7 bead.

All the beads Nos. 1 to 6 are rather larger than most of the Saxon beads of this sort.

I am afraid that I am quite unable to date these beads. There are two periods when beads similar to Nos. 1 to 6 were made. One is La Tène, which in this country might extend up to 50 B.C. or even later; the other is Saxon. Above, I have given a few particulars of the beads and some of the parallels which make it so difficult to date them. The appearance of so many annular beads found in sites dated from Pre-Roman times to the Saxon period, and the appearance of some very definitely shaped amethyst beads over the same periods has led some archaeologists to suggest that the Saxon specimens may all of them be Roman beads used again. I think a more probable explanation is that the manufacture was continued until the later period, although we have no knowledge where.

The beads are preserved in the Museum of Archaeology and Ethnology at Cambridge, to which they were kindly presented by Major Clarke, Chief Engineer to the Middle Level Drainage Commissioners.

The Foraminifera of the Fenland Clays at St. Germans, near King's Lynn.

By W. A. Macfadyen, Sedgwick Museum, Cambridge.

Summary.

THE complete sequence of Fenland deposits at St. Germans consists of five clays interbedded with four peats; the whole is apparently of post-Glacial age, and the later beds at least were laid down in historic times. Fourteen specimens were collected from the clays, and all yielded foraminifera. Forty-one species of these are indigenous, five are derived from the Chalk, and twelve from the Kimmeridge Clay. Of the indigenous species nearly all are forms tolerant of brackish-water, while species intolerant of this are almost lacking. From this fact and from the presence of many fragments of peat in the clays it is concluded that these are of brackish-water origin. From the presence of a proportion of micaceous silt in many of the clays, accompanied by and correlated with foraminiferal species less tolerant of brackish water, occasional ingress of estuarine water is presumed.

Introduction.

Through the efforts of Major Gordon Fowler, the complete section of Fenland deposits proved recently at St. Germans during construction work was studied by Mr. F. H. Edmunds, of H.M. Geological Survey, and a series of specimens collected. The four peats have been studied in much detail by Dr. and Mrs. Godwin, and their results are given in the preceding pages of this issue of the Geological Magazine. Their paper includes Mr. Edmunds' note on the section.

The present paper presents the results of an examination of the foraminifera of fourteen samples of the clays collected by Mr. Edmunds, and which he kindly made available. It is hoped that it will be followed by other contributions dealing with the Fenland foraminifera ; the present conclusions are necessarily of a preliminary nature and subject to confirmation or otherwise in the light of further work. The present investigation has been undertaken in connection with the Fenland Research Committee as a contribution to the study of the Fenland deposits by this body.

Foraminifera from the apparently post-Glacial Fenland deposits were amongst the earliest to be studied in this country, and formed the majority of the material described by Williamson (1)[1] in 1848. They were referred to again by this author in his monograph (2) of 1858, and lists of foraminifera from four samples of Fenland deposits were given by Parker and Jones (3) in 1865. In his 1870 paper, Brady (4) deals mainly with living faunas, but he compares his results closely with those obtained by Parker and Jones in their lists mentioned above. Since that date there appears to have been an absence of published work on the Fenland foraminifera. From further afield in this country, however, foraminifera from various post-Glacial deposits have been listed, mainly by Robertson and by Joseph Wright, in a number of papers. On the Continent, Madsen is the most prominent author to deal with similar material, and his Memoir (5) of 1895 is a most important contribution.

Difficulties of nomenclature of the foraminifera make it often doubtful as to how far lists of different authors can be compared without study of their specimens ; and though a general idea of the fauna can, of course, be obtained, finer comparisons are not seldom impossible.

The following table gives a synopsis of the residues of the clays after washing.

Bed A		B	C		D	E		F			G		H J
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Brown micaceous silt . .	–	–	–	2	–	–	3	3	3	2	3	2	3	–
Peaty Vegetation . .	1	2	–	3	3	3	1	1	–	2	2	2	2	2
Sulphur dioxide on heating	–	–	–	+	+	+	–	–	–	+	–	–	–	–
Particles of red-burnt clay	–	–	–	–	+	+	–	–	–	+	–	–	–	–
Foraminifera { Indigenous .	2	1	–	3	1	2	3	3	3	2	1	2	1	2
Foraminifera { Chalk . .	–	–	–	–	–	1	2	2	2	–	1	2	–	1
Foraminifera { Kimmeridge.	2	–	2	–	–	–	–	–	1	–	–	–	–	–

1 = small quantity ; 2 = some ; 3 = much. From the peat washed from sample 5 was extracted by means of carbon tetrachloride a comparatively large quantity of free sulphur.

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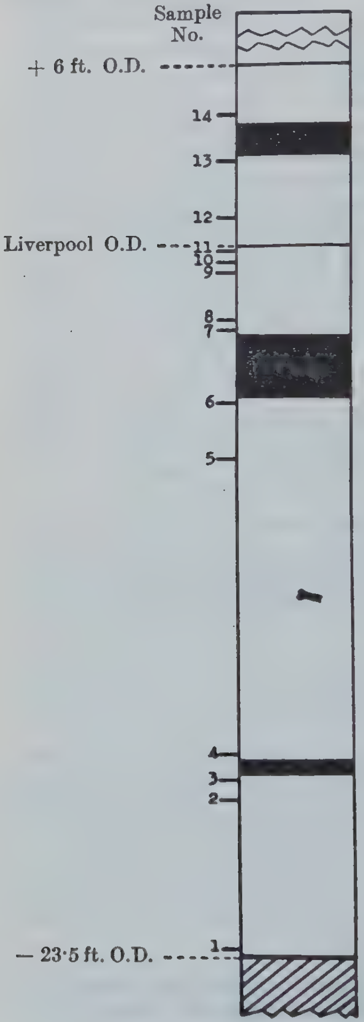
[1] Numbers in parentheses relate to References at the end of this article.

THE CLAY SAMPLES.

The position in the section of the clay samples examined, together with other fossils of importance, is shown to scale in the accompanying Fig. 1, which is plotted from Mr. Edmunds' data.



	12 ft.	Made ground.
J	2 ft.	Blue Clay.
H	1 ft.	Peat.
G	3 ft.	Brown Silty Clay.
F	3 ft.	Blue Clay with *Scrobicularia piperata.*
E	2 ft.	Peat. Seven beads found 2 to 3 inches below the top.
D	12 ft.	Blue Clay, partly mottled brown, with *Cardium edule,* and the tibia of a deer [1] 5 ft. 6 in. above base.
C	½ ft.	Six-inch Peat, with oak-tree stools.
B	6 ft.	Buttery Blue Clay locally with brown sandstone pebbles replacing the top foot of clay; much calcite in sample 2.
A		One-inch Peat.
		Kimmeridge Clay.

FIG. 1.—Section of the Fenland Deposits at St. Germans.

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[1] The deer tibia was submitted to Professor S. H. Reynolds for his opinion, but Mr. Edmunds tells me that Professor Reynolds found it not further identifiable.

The Indigenous Foraminifera.

Bed	A	B		C	D		E		F			G		H J
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1. *Haplophragmoides canariensis* (d'Orb.)	–	–	–	–	–	–	–	–	–	I	–	–	–	–
2. *Trochammina inflata* (Montagu)	–	–	–	C	–	I	V	–	–	I	V	–	–	–
3. *T. inflata* var. *macrescens* Brady	–	–	–	C	–	–	X	V	–	X	–	–	–	–
4. *T. ochracea* (Williamson)	–	–	–	–	–	–	–	–	–	–	–	–	–	I
5. *T. squamata* Jones and Parker	–	–	–	–	–	–	–	–	–	I	–	–	–	–
6. *Bulimina marginata* d'Orbigny	–	–	–	–	–	–	–	–	I	–	–	–	–	–
7. *B.* spp.	–	–	–	–	–	–	I	–	I	–	–	I	–	–
8. *Buliminella elegantissima* (d'Orbigny)	–	–	–	–	–	–	I	X	I	–	–	V	–	I
9. *Reussia spinulosa* (Reuss)	–	–	–	–	–	–	–	–	–	–	–	–	–	I
10. *Virgulina fusiformis* Cushman	–	–	–	–	–	–	I	I	–	–	–	V	–	I
11. *Bolivina* cf. *nobilis* Hantken	–	–	–	–	–	–	I	–	–	–	–	–	–	–
12. *B. dilatata* Reuss	–	–	–	–	–	–	–	–	I	–	–	–	–	–
13. *B. pseudo-plicata* Heron-Allen and Earland	–	–	–	–	–	–	I	–	–	–	–	I	–	I
14. *Lagena catenulata* (Williamson)	–	–	–	–	–	–	–	–	–	–	–	–	–	I
15. *L. clavata* (d'Orbigny)	–	–	–	–	–	–	–	I	–	I	–	I	–	–
16. *L. globosa* (Montagu)	–	–	–	–	–	–	I	–	–	–	–	–	–	–
17. *L. laevigata* (Reuss)	–	–	–	–	–	–	I	V	I	I	–	I	–	I
18. *L. laevis* (Montagu)	–	–	–	–	–	–	–	–	–	–	–	I	–	–
19. *L. lineata* (Williamson)	–	–	–	–	–	–	–	–	–	–	–	–	–	I
20. *L. ovum* (Ehrenberg)	–	–	–	–	–	–	I	–	–	–	–	–	–	–
21. *L. scalariformis* (Williamson)	–	–	–	–	–	–	–	–	I	–	–	–	–	–
22. *L. perlucida* (Montagu)?; (Williamson 1858 fig 7 only)	–	–	–	–	–	–	I	–	–	–	–	–	–	–
23. *L. sulcata* Walker and Jacob	–	–	–	–	–	–	I	I	I	–	–	I	–	I
24. *L. trigono-marginata* Parker and Jones	–	–	–	–	–	–	I	–	? I	–	–	–	–	–
25. *L. williamsoni* (Alcock)	–	–	–	–	–	–	I	–	–	–	–	–	–	–
26. *Nodosaria communis* (d'Orbigny)	–	–	–	–	–	–	I	–	–	–	–	–	–	–
27. *Marginulina costata* (Batsch)	–	–	–	–	–	–	–	–	–	–	–	–	–	I
28. *Cristellaria crepidula* (Fichtel and Moll)	–	–	–	–	–	–	–	–	I	–	–	–	–	–
29. *Sigmomorphina williamsoni* (Terquem)	–	–	–	–	–	–	I	–	–	–	–	–	–	–
30. "*Polymorphina*" sp.	–	–	–	–	–	–	–	I	–	–	–	–	–	–
31. *Uvigerina angulosa* Williamson	–	–	–	–	–	–	I	–	–	–	–	–	–	–
32. *U. asperula* Czjzek	–	–	–	–	–	–	–	–	I	–	–	–	–	–
33. *Discorbis globularis* (d'Orbigny)	–	–	–	–	–	–	I	–	–	–	–	–	–	–

THE INDIGENOUS FORAMINIFERA (*Continued*)

Bed	A	B		C	D		E		F			G		H J
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
34. *D. obtusus* (d'Orbigny) .	I	–	–	–	–	–	V	X	I	–	I	V	–	I
35. *Cibicides lobatulus* (Walker and Jacob) .	–	–	–	–	–	–	–	–	–	–	–	–	–	I
36. *Rotalia beccarii* (Linné)	V	I	–	–	–	C	X	V	X	V	–	V	I	V
37. *Nonion depressulus* (Walker and Jacob).	V	–	–	–	–	–	C	L	C	X	–	L	I	X
38. *Elphidium crispum* (Linné) . . .	–	–	–	–	–	–	–	–	I	–	–	–	–	–
39. *E. excavatum* (Terquem)	I	–	–	–	I	–	X	–	–	–	I	–	–	V
40. *E. incertum* (Williamson) . . .	–	–	–	I	–	–	V	X	X	V	–	X	I	–
41. *E.* sp. cf. *oceanense* (d'Orbigny) . .	–	–	–	–	–	–	V	–	–	–	–	–	–	–

SPECIES DERIVED FROM THE CHALK.

Bed	A	B		C	D		E		F			G		H J
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
42. *Pseudotextularia globulosa* (Ehrenberg) .	–	–	–	–	–	I	V	X	X	–	–	X	–	V
43. *Eouvigerina cretacea* (Heron-Allen & Earland) . . .	–	–	–	–	–	–	I	I	I	–	–	–	–	–
44. *Globotruncana linneiana* (d'Orbigny) . .	–	–	–	–	–	–	–	–	I	–	–	–	–	–
45. *Globigerina aspera* (Ehrenberg) . .	–	–	–	–	–	–	X	X	X	–	–	X	–	V
46. *G. cretacea* (d'Orbigny)	–	–	–	–	–	–	V	–	–	–	–	–	–	–
Chalk Spheres . .	–	–	–	–	–	–	X	X	L	–	I	L	–	V

SPECIES DERIVED FROM THE KIMMERIDGE CLAY.

Bed	A	B		C	D		E		F			G		H J
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
47. *Marginulina radiata* Terquem . .	X	–	X	–	–	–	–	–	I	–	–	–	–	–
48. *Vaginulina flabellata* (Gümbel) ? . .	V	–	–	–	–	–	–	–	–	–	–	–	–	–
49. *V. harpa* (Roemer) .	V	–	–	–	–	–	–	–	–	–	–	–	–	–
50. *V. laminata* (Terquem)	–	–	I	–	–	–	–	–	–	–	–	–	–	–
51. *Cristellaria implicata* Schwager . .	I	–	–	–	–	–	–	–	–	–	–	–	–	–
52. *C. helios* Terquem .	X	–	X	–	–	–	–	–	–	–	–	–	–	–
53. *C. lituoides* Bornemann.	–	–	I	–	–	–	–	–	–	–	–	–	–	–
54. *C. prava* Terquem .	V	–	–	–	–	–	–	–	–	–	–	–	–	–
55. *C. protracta* Bornemann	V	–	V	–	–	–	–	–	–	–	–	–	–	–
56. *C. rotulata* (Lamarck) .	–	–	I	–	–	–	–	–	–	–	–	–	–	–
57. *C. varians* Bornemann .	–	–	–	–	–	–	–	–	–	–	–	–	–	–
58. "*Polymorphina*" sp. .	I	–	I	–	–	–	–	–	–	–	–	–	–	–

Summary of the Foraminifera.

Bed	A	B	C		D	E			F			G		H J
Sample No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Indigenous species . .	4	1	0	3	1	2	24	11	15	9	3	12	3	16
Species derived from the Chalk (including Chalk Spheres) . . .	0	0	0	0	0	1	5	4	5	0	1	3	0	3
Species derived from the Kimmeridge Clay . .	8	0	7	0	0	0	0	0	1	0	0	0	0	0
Total species . .	12	1	7	3	1	3	29	15	21	9	4	15	3	16

The roman numerals in the above list indicate the approximate frequency of occurrence of each form: I = very rare; V = rare; X = frequent; L = common; C = abundant.

The specimens have been deposited in the Sedgwick Museum, Cambridge, on four slides, Regd. Nos. 643–6.

The foraminifera found in the clays proved to be divisible into those indigenous to the deposits and those derived from the Chalk and from the Kimmeridge Clay respectively. It has been explained in a previous paper (6) how these faunas may be differentiated, but in the present instance again there may be doubt as to the correct ascription of a few forms; e.g. *Nodosaria communis*, the single broken fragment of which, recorded as indigenous, may possibly have been derived from the Chalk.

The indigenous foraminifera, which are all living species, give no precise indication of the age of the Fenland deposits, which, on the evidence of the peats, appear to be all post-Glacial. The beads found in Peat E have, unfortunately, yielded no exact archaeological date, but they are valuable in giving some limits to the possible age, which, as regards the latest clays at least, is so recent that they must have been deposited in historic times. The particles of red-burnt clay, recorded from the residues of three samples, suggest the presence of human occupation sites nearby.

With regard to climatic conditions the indigenous foraminifera give no unequivocal assistance, and more reliable results are obtained by a study of the peat floras. The single point which may be significant is the absence from any Fenland deposit I have so far examined of *Nonion orbicularis* and *Elphidium arcticum*, both boreal species, and found in the glacial deposits of East Anglia (6). But since there is no evidence known to me regarding their tolerance of brackish water, their absence might conceivably be due to a lack of this tolerance rather than to a climate too genial for them. Both genera, however, belong to group (iv) (see below), the most tolerant of brackish water.

The indigenous foraminifera are of significance in that the presence in large numbers of some species and the absence of others gives an indication of the conditions under which the Fenland clays were deposited. Foraminifera, excluding the special family of the Allogromiidae, are almost wholly marine organisms, but some genera and species have been found to exhibit a certain tolerance of admixed fresh water. The evidence on which the following remarks are mainly based is given by Brady (4) in his 1870 paper. In his study of foraminifera living at the present day in tidal rivers round the coasts of this country, Brady found that the genera could be divided into groups according to their tolerance or otherwise of admixture of fresh water. His results may be summarized as follows :—

i. Genera intolerant of any admixture of fresh water.
ii. Genera which tolerate a slight admixture but do not thrive.
iii. Genera which tolerate a limited amount and sometimes thrive greatly under such conditions.
iv. Genera which thrive with a large admixture, one or two species in extreme cases living in completely fresh water.

Of the present list of indigenous forms there are included hardly any of group (i), indicating that even the sea-borne forms are of an estuarine nature. *Uvigerina* and *Virgulina*, Brady states, are not " proper " to brackish water ; but *Virgulina fusiformis* is not rare in the Fenland deposits, and may prove to be more tolerant than Brady considered the genus to be. Of group (ii) are *Cristellaria*, *Sigmomorphina*, and *Polymorphina*, all rare forms in the samples. Of group (iii) are *Bolivina*, *Bulimina*, *Discorbis*, and especially *Lagena*, and some of these genera here become numerous. Lastly, group (iv) includes such forms, some of which are most abundant in the Fenland clays, as *Trochammina*, *Rotalia beccarii*, *Nonion depressulus*, and *Elphidium*.

It may be remarked, however, that these results can hardly be taken as more than provisional. Brady gave a general outline of the reaction of genera to brackish water, but not of each species, and certainly one tolerant genus, *Elphidium*, has a species which is little if at all tolerant, *E. crispum* ; a converse case might equally well be true. Before an approach to certainty can be reached, therefore, each species must be studied separately, a task that has not yet been adequately undertaken.

Of the derived foraminifera, the characteristic Jurassic forms come from the Kimmeridge Clay, on which also the section rests, and are fairly common only in samples 1 and 3 of Clay B. On the evidence of their association with a very scanty indigenous foraminiferal fauna almost entirely of group (iv), the Kimmeridge forms appear to come from an outcrop of Kimmeridge Clay exposed to denudation nearby. It may be noted in passing that the determination of the valid names of Jurassic foraminifera is, at the present time, a matter of difficulty, and the names used here are provisional.

The derived Chalk foraminifera are, with a trifling exception, confined to samples 7 to 14, from Clays F, G, and J. All the forms, with the exception of the single specimen of *Globotruncana linneiana*, are of minute species. Associated with them are the tiny chalk spheres likewise derived from the Chalk, but probably of inorganic origin. From their general association with the more marine forms of the indigenous foraminifera, and with silt, these derived Chalk foraminifera probably, I think, came from the marine erosion of Chalk outcrops on the coast, and were brought to be deposited in the clays by the tidal estuarine water flowing up the creeks.

Relation between Indigenous Foraminifera and Silt.

Micaceous silt may be either absent or present to a very variable extent in the Fenland deposits. Silt is very fine sand, the grains of which have a diameter of not more than 0·01 mm., and in the Fens it is usually mica-bearing. Normally, it is of a light-brown colour, but in certain cases it is grey, which is apparently due, as may easily be envisaged under Fenland conditions, to agencies which have caused the reduction of the ferric oxide to the ferrous condition. There appears to be in general a correlation between certain of the foraminifera and the silt. The more frequent are the more nearly marine indigenous species, the greater proportion of silt is found. This relation is particularly evident in the silts which form the roddons, or deposits of ancient waterways in the Fens, described by Major Fowler (7). The conclusion is that the silt is of estuarine origin, in that it has reached its present position in roddons, or disseminated in many of the Fenland clays, by tidal influx of silty estuarine water up waterways such as those which formed the roddons, and thence into the brackish lakes or lagoons in which the clays appear to have been mainly deposited. The point which seems to emerge is that while the silt came up from the estuarine sea the clay is perhaps more of the nature of a freshwater deposit derived directly from the denudation of the land, and most of the Fenland deposits (excluding, of course, the peats, sands, and gravels) consist of a mixture of these two components in varying proportions. The derived Chalk foraminifera at St. Germans, as is in my experience usual in the Fens, appear to be generally associated with the more marine indigenous foraminifera and the silt, as noted above. This point, together with the presence usually of only the smallest species, suggests to me that they are introduced *up* the channels from the sea.

Conclusion.

The conclusions to be drawn from the present study are thus mainly concerned with the conditions under which the Fenland clays were deposited. By far the greater part of the indigenous foraminifera of every sample consists of forms of group (iv), which are tolerant of a comparatively large admixture of fresh water; forms which are less tolerant are either lacking or present in only small numbers. The conclusion seems definite: that these clays were deposited under brackish-water conditions; that is, they are lagoonal or lacustrine clays, but the basins were not completely cut off from the sea. The most nearly fresh-water clays are B and D. After the formation of the 2-foot peat E, there is evidence of appreciably more marine conditions given by the presence of a considerable number of foraminiferal species of group (iii), less tolerant of brackish water, and also of silt. Fluctuation in the proportion of sea-water present seems to be reflected in the greater number of species in samples 7 (particularly), 8, 9, 12, and 14 (more marine conditions); and the lesser variety of forms in samples 11 and 13 (fresher water conditions). It seems that the presence of *Cardium edule* and *Scrobicularia piperata* is probably not opposed to this view, since these (or at least the genera) are capable of living in brackish-water lakes (8). But more definite information on this point is desirable.

The peat beds represent a land surface or shallow marsh conditions, while the clays represent some sort of lacustrine or lagoonal conditions, and the alternation of these beds thus points to fluctuation in the water level. The marine invasions after peats E and H are particularly well marked in the more abundant foraminifera of the more marine groups (iii) and (ii) found in samples 7 and 14.

It should be made clear that the conclusions derived from the study of the deposits of a single locality as St. Germans are only locally applicable, and that until a considerable number of such localities have been studied throughout the Fenlands any more general conclusions must be of a tentative nature. However, it may be mentioned that the conclusions suggested above do, in my experience, agree with the facts observed in other Fenland localities, and have, in fact, been influenced by this other work.

My thanks are due to H.M. Geological Survey in general and to Mr. F. H. Edmunds in particular for the provision of the samples and for information concerning the section; and to Professor O. T. Jones, F.R.S., Mr. A. G. Brighton, and Dr. H. Godwin for helpful criticism of this paper in manuscript.

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CORRESPONDENCE.

LATERITE.

Sir,—Mr. Maufe's letter in the March number of the Geological Magazine encourages me to offer a few more remarks on the subject of laterite. If anyone who is sufficiently interested in the subject will consult Buchanan's original description in *A Journey through the Countries of Mysore, Canara, Malabar, etc.* (vol ii, second edition, published by Higginbotham and Co., Madras, in 1870), it will be found that there are seven references to laterite, on pp. 116, 129, 197, 249, 264, 376, and 381; and that in four of those references granite is mentioned as the associated rock. Moreover, on the 1931 (5th edition) Geological Map of India, sheet 6, the country traversed by Buchanan is shown as recent, older alluvium, "unclassified crystallines," gneiss, Charnockite Series, granite and syenite, with some old sediments. At Salem only is there ultrabasic rock. The inference that the type laterite described by Buchanan is a weathering product of granite or closely allied rocks is strengthened by an official letter I received from the Geological Survey of India in 1930 in which I was informed that Buchanan's laterite is a detrital form varying from "limonitic haematite to argillaceous or siliceous limonite". There is no mention in this letter of the aluminium hydroxide that one would expect as a weathering product of basic rocks. Until we have analyses of specimens from the type localities, therefore, we have some ground for believing that Buchanan described the weathering product of acid rocks in which the amount of aluminium hydroxide is negligible. If he had made his observations on the Deccan Trap, which lies to the north of the area he traversed, he might have named "laterite" something rich in aluminium hydroxide, if it was in use as building material. It may be remembered that I have suggested that generally speaking in weathering the formation of aluminium hydroxide is characteristic of basic rocks while hydrated silicate of aluminium is characteristic of the weathering of acid rocks, even in tropical climates. Dr. E. Parsons, in a review of "The Geology of Malaya" (*Mining Magazine*, December, 1931), says that this is in accordance with his experience in the East Indies, India, and Africa; so I suspect more strongly than ever that we have been on a wrong scent in thinking that the production of aluminium hydroxide from felspars depends on climate.

I have already quoted, in "The Geology of Malaya", M. Blondel and Mr. A. C. de Jongh on this subject.

Mr. Maufe mentions *Laterite and Lateritic Soils*, published by the Imperial Bureau of Soil Science. I had the advantage of meeting the authors of this paper at the Rothamsted Experimental Station shortly before it appeared and am grateful to them for information and for the valuable chemical work that they have done. As Mr. Maufe remarks, soil chemists are establishing a definite type of "lateritic" soil. The definition is based on the silica/alumina ratio in clay fractions. Agronomists have adopted laterite and cradled it with their own offspring "podsol". Unless we want to retain the term in Buchanan's original, utilitarian sense I think we might gracefully acquiesce in this adoption. I have contended before that it is now of little scientific value and I am sure that Buchanan's etymological child is now in excellent hands.

Finally, Mr. Maufe raises the question—is Buchanan's laterite forming at the present day or not ? I cannot give any first-hand evidence about India, but the Malacca laterite, which Dr. Ward mentioned as agreeing exactly with Buchanan's laterite, is certainly forming at the present day and will continue to form as long as there is water in the ground.

J. B. Scrivenor.

RECOVERY OF BROMOFORM.

Sir,—There appears to be no published record of the following simple method of recovery of the bromoform absorbed by sands during the separation of heavy minerals by means of this liquid.

It has been the practice to extract the bromoform from the residues by washing with benzene and then separating the liquids by fractional distillation. In the method here described the residues are washed with methylated spirits. The methylated spirits-bromoform mixture so formed is run into water contained in a separating funnel where the methylated spirits is dissolved in the water and the insoluble bromoform settles to the bottom of the funnel, whence it is run off into a beaker. In order to remove the last traces of water from the bromoform the beaker is kept for a few hours in a desiccator.

The method was first brought to the notice of the writer by Dr. T. Sutton Bowman before his departure for India in October last, and has since been used in the Geology Department of the Imperial College of Science and Technology, where tests have demonstrated the ease with which the bulk of the bromoform can be recovered in this way. The loss of the comparatively cheap methylated spirits is more than compensated by the recovery of the more expensive bromoform.

S. Bracewell.

The Imperial College of Science and Technology,
South Kensington, S.W. 7.
15*th February*, 1933.